UNDERSTANDING COMPONENTS OF MOTOR IMAGERY ABILITY AND THE ASSOCIATION WITH MOTOR PROFICIENCY IN CHILDREN AND YOUNG ADULTS

by

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DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at

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A note regarding the current COVID-19 pandemic situation.

The proposal for this dissertation involved data collection and analysis for 3 individual studies. The minimum requirement for the successful completion of a dissertation in the UTA Department of Kinesiology is 2 studies/articles. Due to changes caused by the COVID-19 pandemic, I will only be presenting two studies for the defense of my dissertation. On March 13, 2020 the University of Texas at Arlington shut down all face-to-face instruction and meetings in light of the coronavirus outbreak. At that point in time I was in the middle stages of data collection for my *third study* and had collected 19 participants for this study while having scheduled another 13 middle-aged and 14 older adults throughout the rest of the month of March. My target goal for participants was at least 30 individuals ages 40-64 and another 30 individuals ages 65 and older. Due to the at-risk population that was involved in my data collection, there was a decision made that my data collection would not resume until it was safe, as decided by the appropriate entities. This study aimed to further explore the lifespan development of MI accuracy and vividness and will be further discussed in chapter 4 of my dissertation defense.

Because of that and the timing of my graduation, we decided to move forward with my dissertation defense using my first two studies which align with the requirements for a Ph.D. in Kinesiology. Due to this, the concept of the dissertation changed from the lifespan development of MI ability to understanding components of motor imagery ability and the association with motor proficiency in children and young adults. The first study (aim 2) was published in 2018 through the Human Movement Science journal and the second study (aim 1) was accepted for publication on June 19, 2020 through the Developmental Neuropsychology journal.

Sincerely,

Chadwick T. Fuchs, M.S

ABSTRACT

UNDERSTANDING COMPONENTS OF MOTOR IMAGERY ABILITY AND THE ASSOCIATION WITH MOTOR PROFICIENCY IN CHILDREN AND YOUNG ADULTS

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Motor imagery (MI) refers to the imagination of a motor task without actual movement execution (Decety & Grézes, 2006) and is believed to represent one’s ability to accurately utilize forward internal models of motor control (Williams et al., 2006). Moreover, MI seems to rely on a network involving motor related regions including fronto-parietal areas and subcortical structures, supporting the view that MI and motor execution are very similar processes (Hétu et al., 2013). This ability has been shown to emerge between 5 and 7 years of age and improve during childhood and adolescence (Molina, Tijus, & Jouen, 2008; Spruijt, van der Kamp, & Steenbergen, 2015). The fine tuning of MI development is commonly observed by 9 years of age (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009) and throughout adolescence (Smits-Engelsman & Wilson, 2013; Skoura, Vinter, & Papaxanthis, 2009). Additionally, to date, most studies addressing MI ability have used the mental rotation (Adams, Lust, Wilson, & Steenbergen, 2017) and mental chronometry (Dahm & Rieger, 2016) paradigms while little research has been done to investigate MI ability through other perspectives, such as accuracy and vividness via questionnaires. Therefore, there is a void in current research literature to where little is known about the development of these perspectives of MI ability across the lifespan and MI’s association with motor proficiency.

Study 1 (Chapter 2) investigates age differences in components of MI ability and the association of motor proficiency. This study investigates differences of MI ability between children (*n* = 101) and young adults (*n* = 140) and the potential association of motor proficiency. Advanced statistical methods were used to compared differences between groups and to determine which dependent variables contributed to the differences. Results indicated that young adults were significantly more accurate and rated their MI significantly more vivid across all subscales in MI ability when compared to children. Furthermore, between-subject effects for MI accuracy showed that young adults had higher scores than children on three of the four subscales and the action subscale significantly predicted motor proficiency.

Additionally, studies have shown that children with Developmental Coordination Disorder (DCD), a condition defined by problems in motor coordination, experience problems with tasks thought to rely on internal models of motor control. Study 2 (Chapter 3) compared components of MI ability between typically developing (TD, n = 51) and children with DCD (n= 42). Results indicated that children with DCD were significantly less accurate than TD children, but there were no significant differences in vividness.

The findings of these investigations provide crucial insight into the development of MI ability and the association between MI ability and motor proficiency. Developing a better understanding of MI ability and the associated effects of MI deficits on an individual’s motor proficiency can help improve motor skill interventions. Future investigations should further explore the development of MI ability into middle-aged and older adults and the unique characteristics of both components of MI ability. In addition, validating the Florida Praxis Imagery Questionnaire (FPIQ; Ochipa et al., 1997) should be conducted in order to ensure that this questionnaire is appropriately capturing MI accuracy. Lastly, further investigation into the subscales and their potential relationship with MI ability and motor proficiency could help create better motor imagery training.

ACKNOWLEDGEMENTS

This work was made possible by the support of my graduate mentor Dr. Priscila Tamplain. Joining the Developmental Motor Cognition lab under Dr. Tamplain's mentorship has allowed for me to develop and grow professionally and personally. Her ability to continuously challenge me in how I think and write, while frustratingly difficult in the moment, has proven to be an incredible gift at the end of it all. I am sincerely grateful to my mentor and my committee members, Dr. Becker, Dr. Ricard, and Dr. Gu for their support and guidance throughout this dissertation process. Last, but not least, none of this could have been possible without the study participants, especially the children (and their parents) who came to the lab and devoted their time.

DEDICATION

This work is dedicated to my wife, Lesli, for her unwavering support provided to me. Without her, none of this would have been possible. Also, this is for my children, Madeline and Mason, who were always waiting by the door to play after a long day.

This work is also dedicated to the many undergraduate students; Susan Hudson, Payton Barnes, Jacquelyn Buitron, Esther Chan, Stephanie Davis, Danielle Pelletier, Sarah Reyno, and Lillian Sheldon, whose help was essential for the completion of this work. Also, to Valerie Martinez, for being an incredible boss and letting me pursue my dreams. Lastly, to my parents, Perry and Melissa, and in-laws, Ric and Teresa, your support and encouragement proved to be a much-needed source of inspiration.

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Chapter 1

INTRODUCTION

Motor Imagery

Motor imagery (MI) is the central topic of this dissertation and refers to the imagination of a motor task without actual movement execution (Decety & Grézes, 2006). MI is closely linked to the ability to generate and utilize internal models of feedforward control (Wolpert & Flanagan, 2001; Williams et al., 2006). Internal models of feedforward control provide stability to the motor system by predicting the outcome of movements before slow, sensorimotor feedback becomes available (Wolpert, 1997;Wilson & Hyde, 2013), and are effective in the training of predictive control (Grush, 2004). The ability to predict outcomes, or predictive and online control, is important in that it is thought to provide fluid, well-coordinated and efficient movements because it allows the performer to make online adjustments based on forward estimates of limb position (Flanagan, Vetter, Johansson, & Wolpert, 2003).

MI has been shown to be connected with motor actions in the brain through a network involving motor related regions, including fronto-parietal areas and subcortical structures of the brain (Hétu et al., 2013). Additionally, MI has been shown to be constrained by the same biomechanical (Kosslyn, Digirolamo, Thompson, & Alpert, 1998) and timing (Choudhury, 2007) constraints as actual movement, in healthy individuals. Behavioral experiments have also revealed a tight temporal coupling between real and imagined action, which is clearly shown by the preservation of Fitts' Law under both real and imagined conditions (Crammond, 1997). This law states that the time taken to perform a movement increases logarithmically with task difficulty, or in other words, a speed-accuracy trade-off (Fitts, 1954). This trade-off has been found to be consistent in the field of motor learning and control. Overall, individuals tend to slow down when we need to increase accuracy of movements and we become less accurate as we begin to move more rapidly. This trade-off has been shown to apply to both executed and imagined movements (Decety, Jeannerod, & Parblanc, 1989; Wilson, Thomas, & Maruff, 2002).

Development of Motor Imagery Ability

The ability to perform MI has been shown to begin to develop between 5 and 7 years of age and continue to 12 years of age (Spruijt, van der Kamp, & Steenbergen, 2015). This continued development, observed at 9 years of age (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009) reflects a refinement of the internal model and multiple studies have agreed to relate this developmental trend to the unfolding capacity to generate and use internal models in predictive and online control (Guilbert, Jouen, & Molina, 2018). Developmentally, Caeyenberghs et al. (2009) provided support that younger children have difficulty generating these forward models of movement that are appropriately scaled to their intrinsic biomechanics. This research showed that forward models develop rapidly between 6 to 10 years of age, which was supported through the heightened coupling between MI and motor proficiency. Taken together, MI has a distinct developmental trajectory that is entwined with the development of movement skill in children (Caeyenberghs et al., 2009). The majority of research exploring the developmental aspects of MI ability have often been limited to participants aged 5 to 12 years (Caeyenberghs et al., 2009; Molina, Tijus, & Jouen, 2008; Spruijt, van der Kamp, & Steenbergen, 2015; Smits-Engelsman & Wilson, 2013; Skoura, Vinter, & Papaxanthis, 2009). While this research has created a solid foundation on our knowledge of the early development of MI ability, to my knowledge, there has not been any research that explores the continuation of this development of MI ability into, and throughout, adulthood.

Motor Imagery and Populations with Motor Deficits

A strong line of research has documented deficits in motor imagery in children with motor deficits (Deconinck, Spitaels, Fias, & Lenoir, 2009; Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson, Maruff, Ives, & Currie, 2001; Wilson, Maruff, Butson, & Williams, 2004). These deficits are thought to be reflective of one's ability to accurately form internal models of control (Skoura, Papaxanthis, Vinter, & Pozzo, 2005). This deficit is commonly shown in difficulties generating or implementing predictive models of actions (Wilson & Butson, 2007) and is encapsulated by a concept known as the internal model deficit (IMD). The IMD supports the notion that children with motor deficits, such as Developmental Coordination Disorder (DCD) rely on slower sensory feedback channels, rather than a reliance on a faster, feedforward control. Further research has supported this by showing slower and clumsier movement patterns, especially in more complicated movements involving motor sequencing in children with DCD (Deconinck et al., 2009, & Williams et al., 2013). Therefore, children with DCD are able to use MI, however, their judgements seem to be compromised by a less well-defined internal model (Deconinck et al., 2009).

DCD is a condition defined by problems in motor coordination development despite their intelligence levels and affects about 2-7% of school-age children (American Psychiatric Association, APA, 2013), with a somewhat higher prevalence in boys than girls (Cairney, Hay, Faught, & Hawes, 2005). While the severity of motor impairment varies, common symptoms include marked delays in motor milestones and clumsiness, typically associated with poor balance, coordination, and handwriting skills. As a result of these symptoms children with DCD tend to have limited athletic ability and thus are more prone to sedentary lifestyles and are more likely to suffer from low self-esteem. To compound these issues in early childhood, nearly half of those diagnosed with DCD in early childhood continue to have difficulties into adolescence and early adulthood (Kirby et al., 2013). Additionally, children with DCD frequently experience a range of comorbid problems including attentional issues (Attentional Deficit Hyperactivity Disorder - ADHD), behavioral issues, language, and psychosocial problems, including anxiety, depression and low self-esteem. Poor motor coordination also results in reduced physical activity participation and lower fitness outcomes in individuals with DCD (Rivilis et al., 2011; Schott, Alof, Hultsch, & Meermann, 2007). Consequently, the risk of obesity and developing cardiovascular diseases is increased (Faught, Hay, Cairney, & Flouris, 2005; Cantell & Crawford, 2008). Therefore, developing a better understanding on the deficits associated with MI ability in children with DCD can further help improve interventions aimed at developing motor proficiency.

Measuring Motor Imagery Ability

MI ability is a multidimensional construct, that can be assessed in terms of factors such as controllability, vividness, and maintenance. Generally, most studies addressing MI ability have used the mental rotation and mental chronometry paradigms. The mental chronometry paradigm involves the explicit use of MI and compares the duration between imagined and executed movements (Dahm & Rieger, 2016). Comparing the duration of the imagined to the executed movements allows for researchers to gauge how well an individual can maintain an image. For example, if the time taken to imagine a movement is similar to the time taken to physically execute the same movement, then that provides indication that the individual has an accurate image. One aspect of mental chronometry is mental congruence (Guillot & Collet, 2005), which states that there is a close correspondence between the time required to mentally perform a given action and that required for its actual execution. While there are several intervening variables such as level of expertise and task complexity, a study using springboard divers found temporal congruence between executed and imagined actions, which may be related to the level of cognitive effort required for the task (Guillot & Collet, 2005). This falls in line with Fitts and Posner (1967), which suggested that as a person's skill level increases, the planning and execution of a movement becomes more automated and involves lower levels of conscious cognition. According to O'Shea & Moran (2015), no study has yet explored the effect of complexity on the temporal congruence between executed and imagined movements among experts.

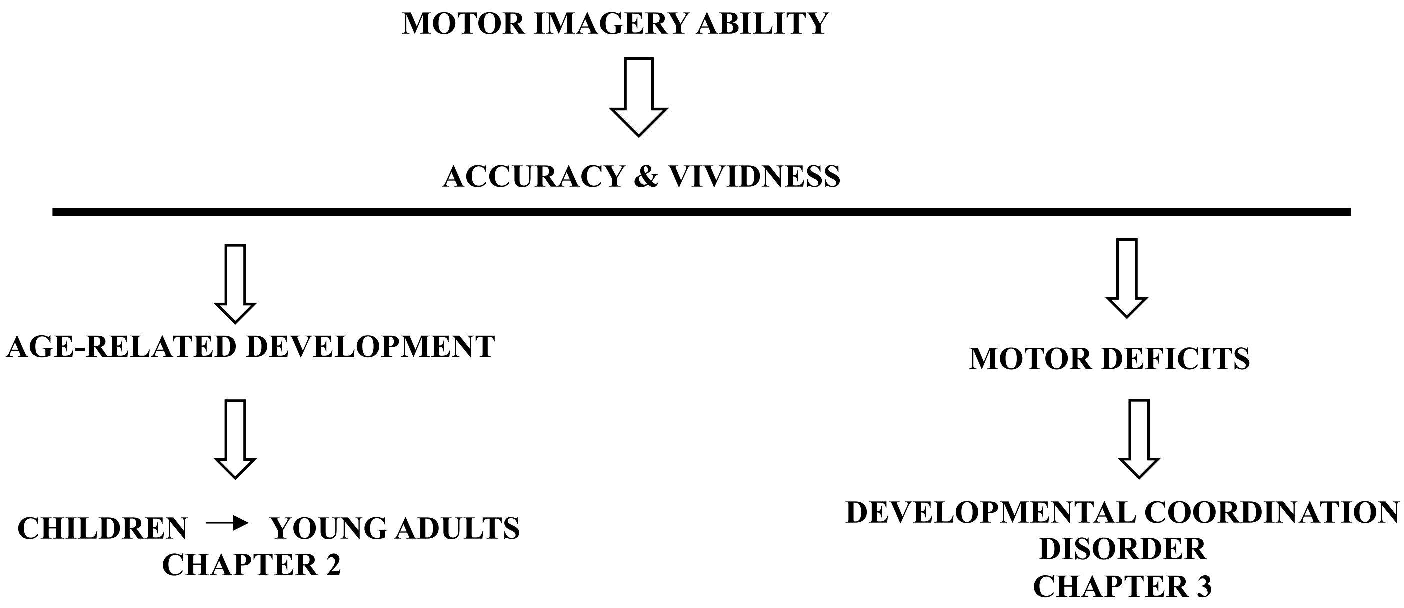
In contrast, mental rotation tasks, require individuals to decide which stimuli are being presented as accurately and quickly as possible (Adams, Lust, Wilson, & Steenbergen, 2017). For example, a hand oriented at different angles will be shown on a computer monitor and the subject must indicate if it is a right or left hand. Each absolute rotation angle (0, 45, 90, 135 and 180) is administered 6 times, for both the right and left hands. Afterwards, it is common to ask the participants how they had decided whether the hand on the screen was left or right in order to help determine the type of strategy used for mental rotation. Results from Wilson et al., (2004) indicated that MI in children with motor deficits is not subject to the same biomechanical constraints as real movements. It appears that these individuals rely on rotating the hands from a third person point-of-view, rather than a first-person point-of-view, which involves visual imagery (not MI) and helped preserve accuracy and enhanced the speed of decision making. Furthermore, the avoidance of biomechanically appropriate movements explained why differences were only found between biomechanically possible rotations.

While research involving the use of mental chronometry and mental rotation tasks are common, little has been done to investigate MI ability from other perspectives, such as accuracy and vividness. One could argue that MI ability has many aspects, and both accuracy and vividness are fundamental for its mastery. MI accuracy can be defined as an individual's ability to correctly imagine the action required to answer a question (Fuchs & Caçola, 2018). On the other hand, MI vividness is defined as the extent a person is able to generate a mental representation of movements (Malouin, Richards, Jackson, Lafleur, Durand, & Doyon, 2007). It is possible to measure accuracy and vividness with the use of questionnaires and these questionnaires provide a unique ability to distinguish and measure the different types of MI ability (kinesthetic, position, action and object) and perspectives (internal, external and kinesthetic). Implementing questionnaires to assess MI ability is appealing because they are easily accessible and relatively fast to asses (Dahm, 2020).

Statement of the problem

Developing a better understanding of MI ability and the associated effects of MI deficits on an individual's motor proficiency can help improve the poor longitudinal health outcomes often associated in individuals with motor deficits (Rivilis et al., 2011; Schott et al., 2013; Faught et al, 2005; Cantell & Crawford, 2008). From a rehabilitation perspective, the increased understanding of the changes of these components of MI ability can help further enhance MI training protocols. Predictive control is used to provide internal feedback of the predicted outcome of an action, which can be used before sensory feedback is available. This predictive control model supports mental practice to learn to select between possible actions, such as MI training. In the field of Sport and Exercise Psychology, MI training has been incorporated through several means. Research has shown that athletes and exercisers use MI to improve concentration (Calmels, Berthoumieux, & d'Arripe-Longueville, 2004), enhance motivation (Hausenblas, Hall, Rodgers, & Munroe, 1999), build confidence (Callow & Waters, 2005), and control emotional responses (Mellalieu, Hanton, & Thomas, 2009). In motor development, MI training has been used in many clinical populations, for example, children with Developmental Coordination Disorder (DCD; Wilson et al., 2016), cerebral palsy (CP; Steenbergen, Crajé, Nilsen, & Gordon, 2009), and ADHD (Lewis, Vance, Maruff, Wilson, & Cairney, 2008). Future implications can involve exploring the unique characteristics of both MI accuracy and vividness.

The following flow chart has been provided to provide a visual overview of this dissertation. The overall purpose of my dissertation is two-fold: 1) explore age-related differences in MI accuracy and vividness and the association of motor proficiency and 2) explore the association between MI accuracy and vividness and motor deficits. Aim 1 of the dissertation involved comparing MI accuracy and vividness between children (aged 7-12) and young adults (aged 18-25) and the association of motor proficiency. Aim 2 of the dissertation involved exploring the differences in MI accuracy and vividness between children with and without DCD.



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Chapter 2

Accuracy and vividness in motor imagery ability: Differences between children and young adults

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Abstract:

Motor imagery (MI) refers to the imagination of a motor task without actual movement execution. The purpose of this study was to compare MI accuracy and vividness, and motor proficiency between children (*n* =101; 7-12 years) and young adults (*n* =140; 18-25 years). Results indicated that young adults were significantly more accurate and rated their MI significantly more vivid than children. For MI accuracy, between-subject effects showed that young adults had higher scores than children on three of the four subscales and the action subscale significantly predicted motor proficiency. These findings indicate that MI ability continues to develop into adulthood.

Keywords: Motor imagery ability, motor proficiency, accuracy, vividness, children, young adults

1. Introduction

Motor imagery (MI) refers to the imagination of a motor task without actual movement execution (Decety & Grezes, 2006). This ability has been shown to emerge between 5 and 7 years of age and improve during childhood and adolescence (Molina, Tijus, & Jouen, 2008; Spruijt, van der Kamp, & Steenbergen, 2015; Butson et al., 2014). The fine tuning of MI development is commonly observed by 9 years of age (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009) and throughout adolescence (Smits-Engelsman & Wilson, 2013; Skoura, Vinter, & Papaxanthis, 2009; Conson, Mazzarella, & Trojano, 2014), which reflects a refinement of the internal model during this period (Guilbert, Jouen, & Molina, 2018). Understanding the development of MI has significant implications in the field of learning and intervention for motor skills (Wilson et al., 2016), injury rehabilitation (Zach, Dobersek, Filho, Inglis, & Tenebaum, 2018), and sport performance (Murphy, Jowdy, & Durtschi, 1990). Therefore, assessing and investigating MI ability is crucial for the understanding of motor behavior (O'Shea & Moran, 2017).

Motor behavior includes every type of movement: from involuntary twitches to goal-directed actions (Adolph & Franchak, 2017). Moreover, motor behavior provides raw material for perception, cognition and social interaction (Gibson, 1988). Learning new or improving motor skills bring new parts of the environment into play and thereby provide new or enhanced opportunities for learning and doing (Adolph & Franchak, 2017). Here, we explored motor behavior in the context of motor proficiency, defined as an adequate or appropriate level of motor skills for a given age. Hétu et al. (2013) has shown that MI is connected with motor actions in the brain through a network involving motor related regions, including fronto-parietal and subcortical structures of the brain. This connection has also been supported through neuroimaging studies, which have shown overlapping neural activity during the actual production of a movement and MI of the same movement (Lacourse et al., 2005; Hanakawa et al., 2008). Furthermore, similar constraints such as biomechanical (Kosslyn, Digirolamo, Thompson, & Alpert, 1998) and timing (Choudhury, Charman, Bird, & Blakemore, 2007) have been shown between motor execution and MI.

The concept of MI is based on the notion of internal models. Internal models of feedforward control provide stability to the motor system by predicting the outcome of movements before slow, sensorimotor feedback becomes available (Wolpert, 1997). They are useful because they provide a means of rapid online correction (Wilson & Hyde, 2013) and are effective in the training of predictive control (Grush, 2004). A strong association between a deficit in predictive and online control and a reduced ability to imagine motor actions has been shown in previous research (Adams, Lust, Wilson, & Steenbergen, 2014; Fuelscher, Williams, Enticott, & Hyde, 2015). This said deficit in predictive and online control is known as the internal modeling deficit hypothesis (IMD; Wilson & Butson, 2007), which states that individuals with motor deficits have difficulty generating or using predictive estimates of body position as a means of correcting actions in real time. Individuals who are unable to anticipate the consequences of action are reliant upon slower feedback control of sensory inputs (Pisella et al., 2009), which then produce slow, effortful, and inaccurate movements (Wilson et al., 2013). The association between deficits in motor proficiency and MI has been supported through an extensive line of research involving children with Developmental Coordination Disorder, a disorder of poor motor proficiency (DCD; Deconinck, Spitaels, Fias, Lenoir, 2009; Maruff, Wilson, Trebilcock & Currie, 1999; Williams, Thomas, Maruff, Butson & Wilson, 2006; Williams, Thomas, Maruff & Wilson, 2008; Wilson, Maruff, Ives & Currie, 2001; Wilson, Maruff, Butson, & Williams, 2004; Fuchs & Caçola, 2018). For example, children with DCD are able to rely on MI, however, their judgements seem to be compromised be a less well-defined internal model (Deconinck et al., 2009).

To date, most studies addressing MI ability have used the mental rotation and mental chronometry paradigms. The mental chronometry paradigm involves the comparison of the duration between imagined and executed movements (Dahm & Rieger, 2016). In contrast, mental rotation tasks require individuals to decide which stimuli are being presented as accurately and quickly as possible (Adams, Lust, Wilson, & Steenbergen, 2017). For example, a hand oriented at different angles will be shown on a computer monitor and the subject must indicate if it is a right or left hand. However, little has been done to investigate MI ability from other aspects, such as accuracy and vividness. One could argue that MI ability has many aspects, and both accuracy and vividness are fundamental for its mastery. It is possible to measure accuracy and vividness with the use of questionnaires and these questionnaires provide a unique ability to distinguish and measure the different dimensions of MI ability (kinesthetic, position, action and object) and perspectives (internal, external and kinesthetic). Implementing questionnaires to assess MI ability is appealing because they are easily accessible and relatively fast to assess (Dahm, 2020). Here, we propose to explore an age-related perspective of these two facets of MI.

MI accuracy can be defined as an individual's ability to correctly imagine the action required to answer the question (Fuchs & Caçola, 2018). On the other hand, MI vividness is defined as the extent a person is able to generate a mental representation of movements (Malouin et al., 2007). We used two paradigms to study MI accuracy (Florida Praxis Imagery Questionnaire; Ochipa, et al., 1997) and MI vividness (*Movement Imagery Questionnaire – Children*; Martini, Carter, Yoxon, Cumming, & Ste-Marie, 2016, and the *Movement Imagery Questionnaire- 3rd edition*;

Williams et al., 2012) in children and young adults. The purpose of the present study was to 1) compare MI accuracy and vividness between children and young adults, and to 2) explore the role of motor proficiency on MI. Based on previous studies, we expected that young adults would display significantly higher MI accuracy and rate their MI significantly more vivid than children, due to a continued development of MI ability into young adulthood. Additionally, due to the refinement of internal models, we expected that individuals with appropriate (average) motor proficiency would have greater MI ability than those with lower motor proficiency. Developing a better understanding of MI ability and the associated effects of MI deficits on an individual's motor proficiency can help improve motor skill interventions.

2. Methods

2.1 Participants

A total of 101 children (51 boys and 50 girls) ranging from 7 to 12 years of age (M_{age} = 9.97, *SD* = 1.71) and 140 young adults (50 men and 90 women) from 18 to 25 years of age (M_{age} = 21.70, *SD* = 1.82) from a large metropolitan area were recruited for this study. These participants were recruited primarily through contact in multiple undergraduate classes at a large University. Participants in the children group were recruited through word of mouth and flyers posted at the university and surrounding areas. Most children were somewhat related to students at the university in which the study was conducted (family members, friends, neighbors). None of the participants, or parents of children, reported any conditions (such as Autism Spectrum Disorder (ASD), Dyslexia, cerebral palsy, hemiplegia, or muscular dystrophy). Additionally, none of the participants had any known injuries.

The experimental protocol for both groups was approved by the Institutional Review Board (IRB) for the ethical treatment of human subjects. Children (and their parents) and young adults were informed of the experimental procedures and provided either consent or assent prior to participation.

2.2 Measures

2.2.1 Motor Proficiency

Motor proficiency was measured in two different ways. For children, the *Movement Assessment Battery for Children – 2nd edition (MABC-2*, Henderson, Sugden & Barnett, 2007) was administered. For adults, we administered the *Bruininks-Oserestky Test of Motor Proficiency* (*BOT-2*; Bruininks & Bruininks, 2005). We decided to use the MABC-2 to measure motor proficiency in children due to it being widely considered the gold standard for identifying motor difficulties in children.

The MABC-2 is a standardized assessment tool that requires a child to perform motor tasks to measure potential motor impairment in children aged 3 years to 16 years. The assessment is divided in three age bands: Age Band 1: 3-6 years, Age Band 2: 7-10 years and Age Band 3: 11-16 years, here, we used age bands 2 and 3. Within each age band, there are eight tasks grouped under three subscales: manual dexterity, aiming and catching, and balance. Each age-band presents similar tasks to be performed and are adjusted for age. Additionally, all scores obtained from these age bands are standardized so that percentile scores can be compared across ages. MABC-2 typically takes anywhere between 20-40 minutes to be completed, depending on the age of the child. Once all tasks are completed, each child’s individual scores are converted to standardized scores and then mapped onto a “traffic light” system, which shows whether or not the child falls into the normal range (green), “at risk” category requiring further monitoring (amber) or is highly likely to have a more serious movement problem (red). According to the manual, individuals who score on the red and amber zone (16th percentile and lower) are recognized as having below average motor proficiency, while those scoring in the green zone are considered having, at minimum, average motor proficiency (Henderson et al., 2007). Henderson et al. (2007) provided evidence suggesting favorable psychometric properties for the MABC-2, with a reliability coefficient of 0.80 for the total test score and coefficients ranging from 0.73 to 0.84 for the individual component scores.

The BOT-2 is an individually administered measure of fine and gross motor skills of children and youth, 4- through 21 years of age. It is intended for use by practitioners and researchers as a discriminative and evaluative measure to characterize motor performance, specifically in the areas of fine manual control, manual coordination, body coordination, and strength and agility. According to the manual, individuals who score at and below the 17th percentile are recognized as having below average motor proficiency, while those scoring above the 17th percentile are considered having, at minimum, average motor proficiency (Bruininks & Bruininks, 2005). The BOT-2 has both a complete and short form. For the purpose of this study, only the short form was used.

2.2.2 MI Accuracy

MI accuracy was measured using the using the *Florida Praxis Imagery Questionnaire* (FPIQ, Ochipa et al., 1997). The FPIQ is an assessment used to determine general ability of the individual to imagine motor actions. It consists of four subscales (kinesthetic, position, action, and object); each designed to evaluate different aspects of tool and object use. The kinesthetic subscale requires the participant to image which joint moves the most or least during a given action. The position subscale involves imagining the spatial position of the hand in relation to either the object or body parts of the person completing the action. The action subscale involves imagining the motion of the limb when performing an action. Finally, the object subscale involves imagining the object, presented within the question, used in an action. Correct answers indicate that the participant is able to correctly imagine the action required to arrive at the answer. Responses for each subscale are scored on a range of 0-10 points (correct answers). Total scores are calculated by adding the total correct scores within each subscale and dividing by the total ten questions, the total score is presented in a percentage form. This questionnaire is formatted in a way that the same imagery-based question is asked in different ways for each one of the subscales. For example, a general question for imagery would be "Imagine you are using a pair of scissors". In order to target the kinesthetic subscale, the question would be "which joint moves more, your shoulder or your wrist?", and "which is higher, your thumb or your index finger?" would represent the position subscale.

2.2.3 *MI Vividness*

MI Vividness was measured using the *Movement Imagery Questionnaire - Children* (MIQ-c, Martini et al., 2016) and the *Movement Imagery Question- 3rd edition* (MIQ-3, Williams et al., 2012). The MIQ-C is an adaptation for children between 7 and 12 years of age of the Movement Imagery Questionnaire – 3 (MIQ-3; Williams et al., 2012) to measure visual (internal [IVI], external [EVI]) and kinesthetic imagery (KI) ability. Instructions are read to participants and pictures are used to help children understand the different types of imagery ability being tested and the rating scale employed. The questionnaire consists of twelve items and four simple movements (knee raise, arm movement, waist bend, and jump). For each item, participants first physically perform the movement and then imagine the movement using IVI, EVI, or KI. Then they rate the ease or difficulty of imagining each movement on a 7-point Likert scale, with 1 representing "very hard to see/feel" and 7 representing "very easy to see/feel". A total of 28 points for each imagery perspective is possible and final scores are calculated by taking the average score of each perspective. The maximum score possible is 7, while the minimum score is 1. Scores from the MIQ-c and MIQ-3 have been shown to be a valid and reliable measures of motor imagery vividness (Martini et al., 2016; Williams et al., 2012).

2.3 Procedures

All participants were tested individually in a laboratory with only the primary investigator and research assistants present. Complete testing lasted about 45 minutes. Every child was tested with the MABC-2, then with the MIQ-c and FPIQ and every young adult was tested with the BOT-2, then the MIQ-3 and FPIQ. All participants were allowed to take as many breaks as needed throughout the testing procedures.

2.4 Data Analysis

Motor proficiency was determined by percentile scores on either the MABC-2 (children) or the BOT-2 (young adults). Additionally, each assessment of MI ability yielded scores for each subscale. In order to compare differences between children and young adults for MI accuracy and vividness and within the subscales of the two questionnaires, two separate one-way multivariate analyses of covariance (MANCOVA) were conducted. The first MANCOVA examined the effect of age on all four subscales of MI accuracy (kinesthetic, action, object, and position) and the second tested the effect of age on all three subscales of MI vividness (KI, IVI, and EVI). As a continuous variable, motor proficiency was treated as a covariate in both analyses. Significant main effects in the MANCOVA were followed up with univariate tests to determine which dependent variables contributed to the differences. All analyses were conducted using SPSS Version 25.0 (SPSS Inc., Chicago, IL).

3. Results

3.1 Group characteristics

Table 1 provides results for both populations and their motor proficiency and MI accuracy and vividness. Results showed that the action subscale was scored highest for both age groups, followed by position, object and kinesthetic within MI accuracy. For MI vividness, the kinesthetic subscale was rated less vivid for both groups. Furthermore, the kinesthetic imagery subscale for both MI accuracy and vividness was the least accurate and rated least vivid for both groups. The following sections will further explain the differences found within both MI accuracy and vividness.

3.2 MI accuracy

Figure 1 provides results for age and MI accuracy. There was a statistically significant effect for age, $\Lambda_{\text{Wilk's}} = .68$, $F\ (4, 235) = 27.34$, $p < .01$, $n_p^2 = .32$. Between-subjects effects showed that young adults had higher scores than children on three of the four subscales; position, $F\ (1{,}238) = 72.18$, $p < .01$, $n_p^2 = .23$, action, $F\ (1{,}238) = 48.11$, $p < .01$, $n_p^2 = .17$, and object, $F\ (1{,}238) = 31.43$, $p < .01$, $n_p^2 = .12$. There was no significant difference on the kinesthetic subscale ($p = .08$) between the age groups. There was also a significant effect of the covariate, motor proficiency, $\Lambda_{\text{Wilk's}} = .95$, $F\ (4, 235) = 2.89$, $p = .02$, $n_p^2 = .05$. To examine the effect of subscales of MI accuracy on motor proficiency, a regression was conducted with the four subscales as predictors of motor proficiency. Results indicated that the overall model was significant, $R^2 = .06$, $F(4, 236) = 3.43$, $p = .01$. Figure 2 provides a scatterplot displaying the means for action, which significantly predicted motor proficiency, $b = 40.98$, $t(236) = 2.83$, $p < .01$, $sr^2 = 0.03$. Kinesthetic, position, and object were not significant predictors of motor proficiency.

Insert Table 2 about here

3.3 MI vividness

Figure 3 provides results for age and MI vividness. There was a statistically significant effect for age, $\Lambda_{\text{Wilk's}} = .88$, $F\,(3, 236) = 11.27$, $p < .01$, $n_p^2 = .13$. Between-subjects effects indicated that young adults scored higher than children on all three subscales; KI, $F\,(1{,}238) = 29.29$, $p < .01$, $n_p^2 = .11$, IVI, $F\,(1{,}238) = 22.12$, $p < .01$, $n_p^2 = .09$, and EVI, $F\,(1{,}238) = 8.72$, $p = .01$, $n_p^2 = .04$. The covariate (motor proficiency) did not have a significant effect, $\Lambda_{\text{Wilk's}} = .99$, $F\,(3, 236) = .69$, $p = .57$, $n_p^2 = .01$.

Discussion

The purpose of the study was to compare MI accuracy and vividness between children and young adults and to explore the role of motor proficiency on MI in both age groups. Our results confirmed our expectations that young adults were significantly more accurate and rated their MI significantly more vivid across all subscales in MI ability when compared to children. Additionally, results indicated that motor proficiency had an effect on the action subscale for MI accuracy. We discuss these results in more detail while comparing them to previous findings and discuss potential practical implications of the study.

We confirmed the hypothesis for the first aim of the study, that there would be age-related difference in both MI accuracy and vividness. MI accuracy, as measured by the FPIQ, involves determining the general ability of an individual to imagine motor actions. It requires an individual to rely on their actual motor proficiency to make decisions on action representation. Similar to the *Theory of Neuronal Group Selection* (Edelman, 1987), this development may be experience-dependent, especially through perceptual-motor exploration or the *Dynamic Systems Theory* (Thelen, 1992; Thelen, 1995; Thelen & Smith, 1994), where new motor skills are acquired through continuous action-perception coupling. It's possible that some of the actions referenced in the FPIQ may not have been experienced by some of the children, such as winding up a car window (electric windows are typically standard now), using a pencil sharpener (many are electric now), and turning on a water faucet (adults may have experienced more types of faucet handles). This could potentially be an explanation as to why their accuracy is lower when compared to young adults. In other words, a young adult has potentially had more opportunity for exposure to a greater amount of experiences to motor actions, developing more efficient internal models of feedforward control.

The significant differences found within MI vividness confirmed our hypothesis that young adults would rate their MI significantly more vivid than children. Both the MIQ-3 and MIQ-c do not require for the individual to be accurate with their MI, but simply to imagine the motor skills. While this current study found significant differences between age and all three subscales of MI vividness, this finding could further support the thought that as individual's get older their awareness of their motor abilities is similar to their actual motor abilities. Previous research has explored MI vividness in aging populations, with results showing MI vividness being similar in younger (M_{age} = 22.9) and older adult (M_{age} = 72.4) populations (Saimpont, Malouin, Tousignant, & Jackson, 2015). Additionally, similar levels of MI vividness results were found in young (M_{age} = 26.0), middle-aged (M_{age} = 53.6), and older (M_{age} = 67.6) populations (Malouin, Richards, & Durand, 2010). Malouin et al. (2010) showed that young and middle-aged groups had higher visual than kinesthetic motor imagery scores, indicating a loss of visual motor imagery dominance in the elderly group. We would like to point out that these two studies used the Kinesthetic and Visual Imagery Questionnaire (KVIQ; Malouin, Richards, Jackson, Lafleur, Durand, & Doyon, 2007), while we used both the MIQ-3 and MIQ-c. Results from Schott (2012) found the young population (20-30 years) to be significantly more vivid than both of the older (70-79 years and ≥ 80 years) populations. These differences along with those observed in the present study suggest that further exploration into the development of MI vividness across the lifespan is warranted, in order to further understand the developmental progression of MI vividness and changes in perspectives of MI vividness (internal, external and kinesthetic) as individuals age.

Interestingly, our results showing kinesthetic imagery (KI) as the least accurate and rated as the least vivid is supported by previous studies (Hall & Martin, 1997; Wilson, Maruff, Ives, & Currie, 2001; Chang & Yu, 2016; Martini et al., 2016). KI seems particularly important to the development of motor skills since it involves the sensations of how it feels to perform a task (Jeannerod, 1997). Through an ALE meta-analysis, Hétu et al. (2013) further supported these findings by showing that KI involves a more extensive neural network when compared to visual MI. These results add to the literature by establishing that KI, regardless of the aspect (accuracy or vividness), may be the most difficult imagery for both children and young adults, and perhaps warrant more focus and time spent practicing it in order to be developed.

A second interesting finding is related to how both children and young adults performed the same on all four subscales of MI accuracy. In other words, both groups scored the lowest on the kinesthetic subscale, followed by object, position and then action. This presents a consistent pattern in which ability within the subscales of MI accuracy appear to remain stable into early adulthood. Action representation, or the representations of the body and its kinematics, is a component of the internal forward model (Wolpert, Ghahramani, & Jordan, 1995). The notion that the action representation system is still developing during adolescence has consequences for the understanding of typical development of control of thought and action, and may be useful for understanding motor impairment in developmental disorders, such as DCD (Choudhury, Charman, Bird, & Blakemore, 2006). To date, we are not aware of any studies that have explored the unique differences within the subscales of the FPIQ. This can significantly aid in the understanding of the development of MI ability as well as the potential causes of MI deficit in populations with motor difficulties.

Measuring MI ability through questionnaires and motor proficiency through observation of motor ability are two distinct things. While MI accuracy, as measured by the FPIQ, involves determining the general ability of an individual to imagine motor actions (Fuchs & Caçola, 2018), it may be that general motor proficiency may only influence the action component of MI accuracy. In order to understand this further, it is necessary to explore the general nature of the questions in the action subscale for the FPIQ. For example, one question reads ‘Imagine you are using a pair of scissors, does your hand move toward or away from your body’. That question requires an individual to imagine using a pair of scissors and accurately predict the appropriate movement pattern. This specific type of question could potentially be eliciting a greater reliance on the feedforward model of control and therefore is able to better distinguish the developmental differences between children and young adults. One possible explanation of the lack of significance found between the other components of MI accuracy could be the differences between the motor skills that are either imagined or performed in the assessments. Both the MABC-2 and BOT-2 are measures of general motor proficiency, they measure motor proficiency via manual dexterity, fine and gross motor abilities, strength and agility (BOT-2) and aiming and catching (MABC-2). While these assessments are great for measuring general motor proficiency, they appear to be poor in assessing daily living skills, which are used in the FPIQ. For example, these daily living skills include using scissors, writing with a pencil, using a seatbelt, eating with a spoon, zipping up a jacket. In general, the MABC-2 and BOT-2 measure motor ability in different context than the FPIQ. In order to better explore the role of motor proficiency on MI ability we encourage further exploration on the comparison of motor skills that are being imagined and performed within the MI questionnaires and motor proficiency assessments. This could help determine whether matching the motor skills between the two would help clarify the role of motor proficiency on MI ability.

While this novel study was successful in showing that MI accuracy and vividness continues to develop into young adulthood, it presents multiple limitations. One limitation is that there have been no validation studies involving the FPIQ. We suggest that future work should involve validating the FPIQ and potentially updating the instrument. Another possible limitation is that these MI questionnaires may elicit MI differently than paradigms such as the mental rotation task and are action specific, which may be influenced by action expertise (Dahm, 2020). In addition, we did not assess the development of MI ability directly, but instead compared participants of different ages. It is possible that additional differences between groups might result from other variables such as gender (Hoyek, Champely, Collet, Fargier, & Guillot, 2009), maturity, school programs, and life experiences (Casey, Colon, & Goris, 1992). Another concern is that both the children and young adults did not complete the same motor proficiency assessment. We determined that the MABC-2 was the most suitable instrument to use with the children because the BOT-2 does not discriminate motor proficiency in children as well (Lane & Brown, 2014). Lastly, there may be a concern that some of the young adults were older than the age range for the BOT-2 (between ages 4 and 21). We would like to note that the BOT-2 is the only test of motor proficiency for individuals in this age range and no significant differences were found between 18-21 and 22-25-year-olds. However, we believe that our findings outweigh the limitations by showing that MI accuracy and MI vividness continue to develop into young adulthood.

In conclusion, our findings indicate that young adults are significantly more accurate and rate their MI significantly more vivid across all subscales in MI ability when compared to children. Additionally, results indicate that the action subscale for MI accuracy significantly predicted motor proficiency. Furthermore, the kinesthetic subscale of both MI accuracy and vividness was scored lower than all other subscales while similar trends were found between young adults and children in the MI accuracy and vividness abilities. These findings indicate that the MI accuracy and MI vividness continue to develop into young adulthood. Further exploration is needed into the impact of motor skill interventions on the development of MI, the unique nature of MI accuracy and vividness, and the potential relationship between measures of MI ability and motor proficiency.

Table 1

Group characteristics (mean and SD) of participants included in the study

Variables	MABC-2/ BOT-2	MI Accuracy				MI Vividness		
		Kinesthetic	Position	Action	Object	Kinesthetic	IVI	EVI
Children (n=101)	31.42 (24.15)	.62 (.12)	.75 (.14)	.82 (.13)	.71 (.15)	5.05 (1.21)	5.39 (1.16)	5.58 (.99)
Young Adults (n=140)	35.72 (21.36)	.65 (.14)	.89 (.10)	.91 (.08)	.80 (.10)	5.88 (1.09)	6.04 (.91)	6.00 (1.13)

Note. MABC-2- Movement Assessment Battery for Children- 2nd edition percentile scores; BOT-2- Bruinicks-Oserestky Test of Motor Proficiency- 2nd edition percentile scores; MI accuracy as measured by the Florida Praxis Imagery Questionnaire (FPIQ); MI vividness as measured by the Movement Imagery Questionnaire for Children & the Movement Imagery Questionnaire- 3rd edition (MIQ-C & MIQ-3).

Table 2

Regression of MI Accuracy Subscales on Motor Proficiency

MI Accuracy	*b*	*t*	*p*	95% CI	sr^2
Kinesthetic	-8.33	-0.73	.466	-30.78, 14.14	.002
Position	5.46	0.46	.647	-17.99, 28.91	.001
Action	40.98	2.83	.005	12.40, 69.56	.032*
Object	7.29	0.60	.552	-16.80, 31.38	.002

Note. Predictor was significant at: * = $p < .01$

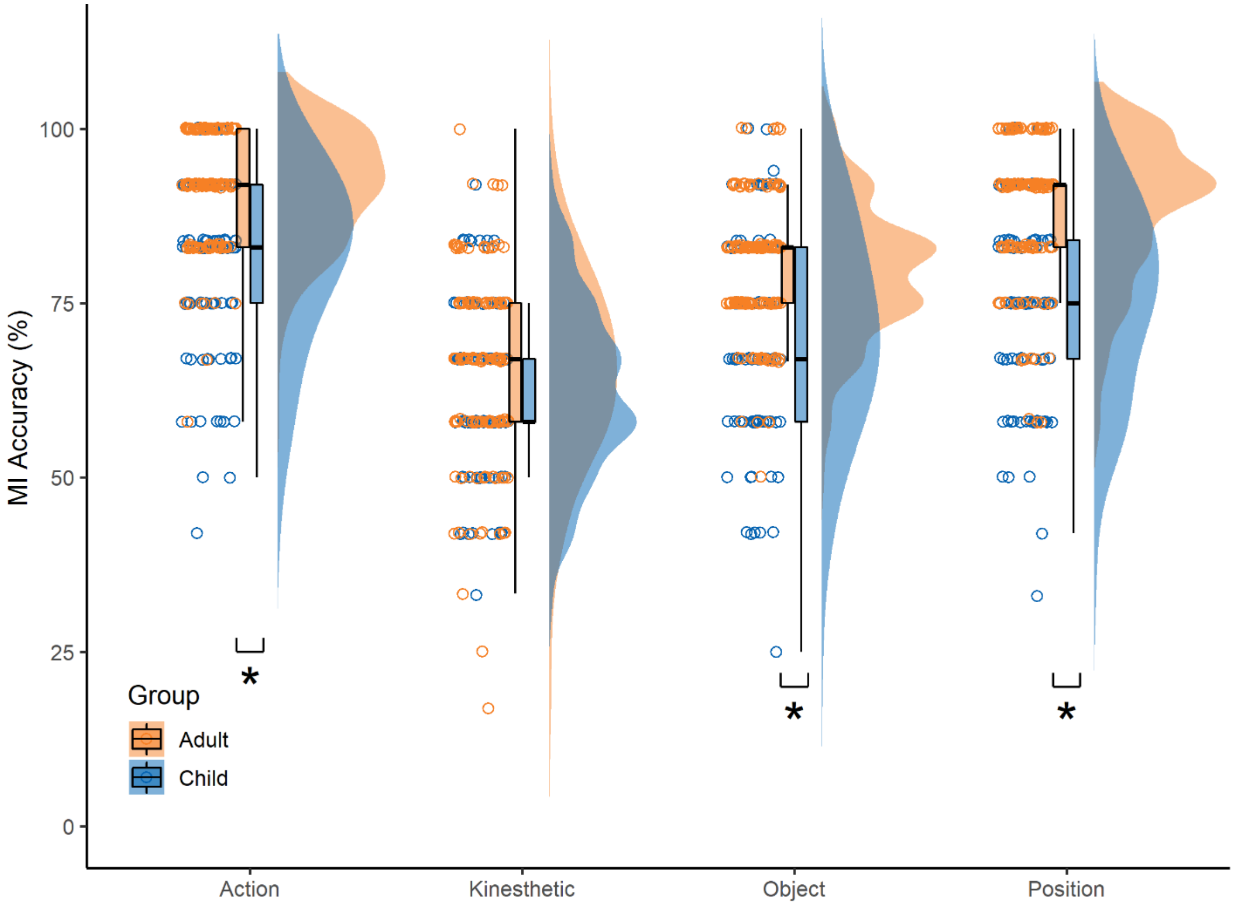

Fig. 1. Raincloud plot displaying mean and standard deviation for MI accuracy and age. *Note*. Range of scores for FPIQ can be 0% (answered all questions incorrectly) to 100% (answered all questions correctly).

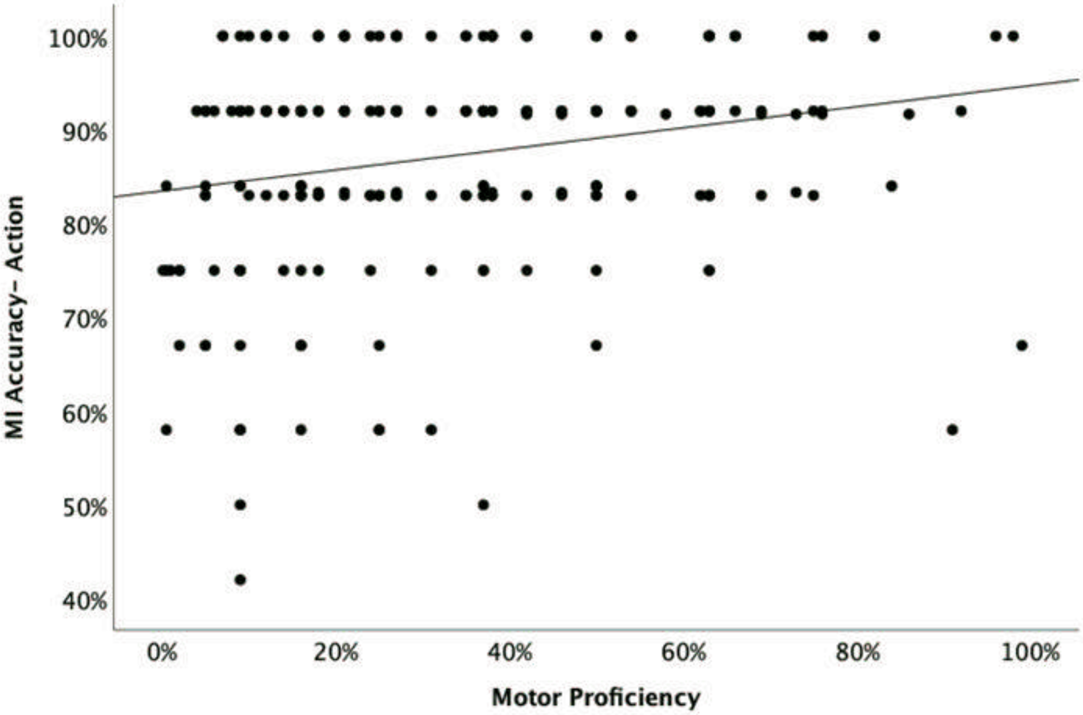

Fig. 2. Scatterplot displaying means for MI accuracy subscale Action and motor proficiency. *Note*. Range of scores for FPIQ can be 0% (answered all questions incorrectly) to 100

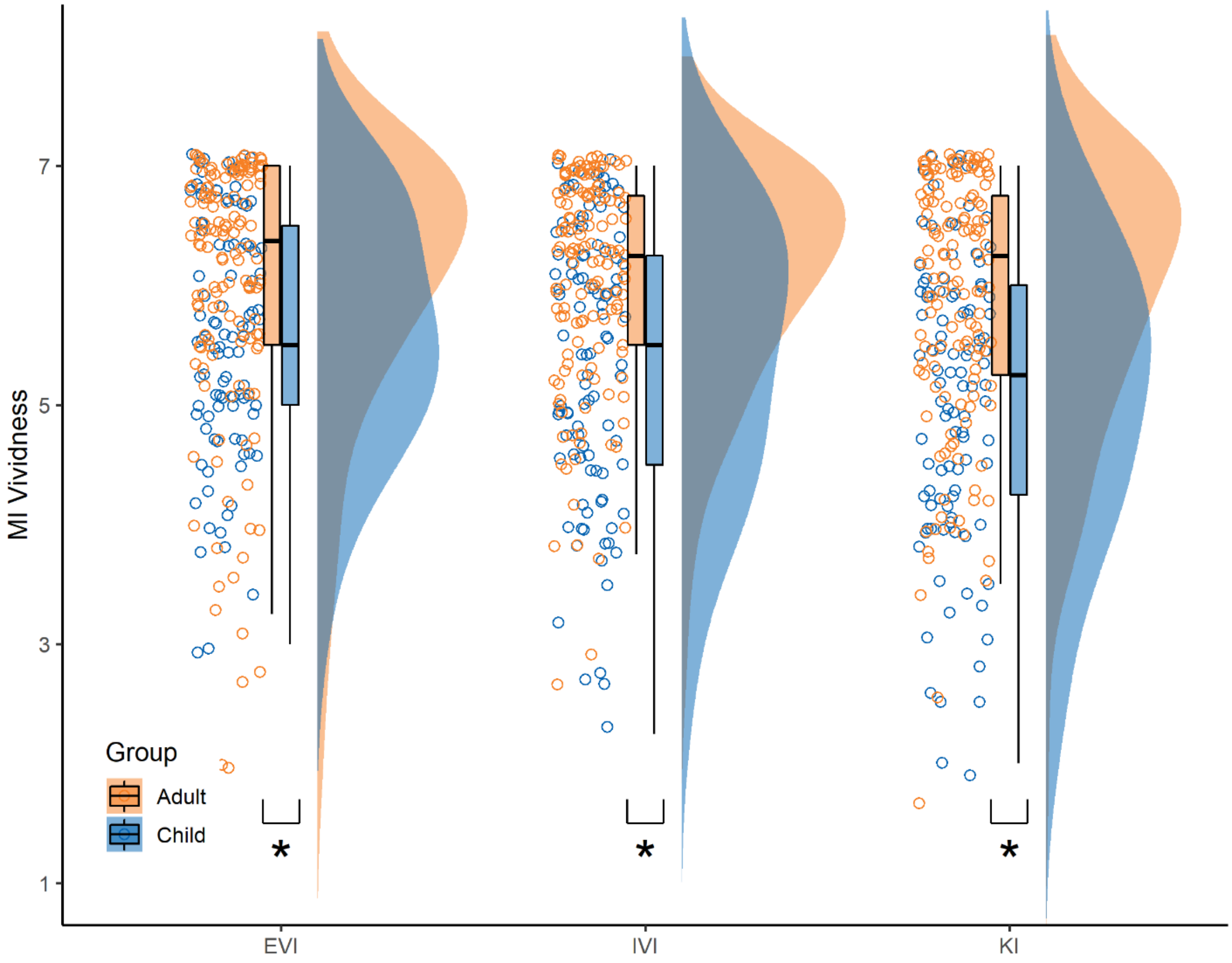

Fig. 3. Raincloud plot displaying mean and standard deviation for MI vividness and age. *Note.* Range of scores for MIQ-c & MIQ-3 can be 1 (very hard) to 7 (very easy).

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Chapter 3

Differences in accuracy and vividness of motor imagery ability in children with and without Developmental Coordination Disorder

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Abstract

Motor imagery (MI) provides a unique window on the integrity of movement representation. Studies have shown that children with Developmental Coordination Disorder (DCD) experience problems with tasks thought to rely on an internal model of movements. Therefore, the purpose of this study was to compare MI accuracy and MI vividness between typically developing (TD) and children with DCD. Ninety-three children with ages between 7 and 12 years (TD: n = 51; DCD: n = 42) were tested with the Movement Imagery Questionnaire (MIQ-c) to assess MI vividness and the Florida Praxis Imagery Questionnaire (FPIQ) to assess MI accuracy. To compare differences between the groups for each assessment and in the subscales, two separate general linear model analyses were conducted: A 2 x 3 (Group [TD, DCD] x Subscales [internal visual imagery, external visual imagery, kinesthetic imagery]) for MI vividness and a 2 x 4 (Group [TD, DCD] x Subscales [position, object, kinesthetic, action]) for MI accuracy. Results indicated that children with DCD scored significantly lower ($p < .05$) on MI accuracy than TD children, but there were no significant differences between the groups on MI vividness. Additionally, there were significant differences in the subscales for both measurements of MI. Specifically, results showed lower scores overall for the kinesthetic subscale. These findings indicate that the MI deficit seen in children with DCD is probably associated with MI accuracy, not MI vividness. These results suggest the need of further exploration into specific measurements of MI in children with DCD.

1. Introduction

Developmental Coordination Disorder (DCD) is a condition that defines children with problems in their motor coordination development despite their intelligence levels and affects about 2-7% of school-age children (American Psychiatric Association, APA, 2013). While the severity of motor impairment varies, common symptoms include marked delays in motor milestones and clumsiness, typically associated with poor balance, coordination, and handwriting skills. A strong line of research has documented deficits in motor imagery in children with DCD (Deconinck, Spitaels, Fias, & Lenoir, 2009; Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson, Maruff, Ives, & Currie, 2001; Wilson, Maruff, Butson, & Williams, 2004).

Motor imagery (MI) refers to the imagination of a motor task without actual movement execution (Decety & Grèzes, 2006), and is believed to represent one's ability to accurately utilize forward internal models of motor control (Williams et al., 2006). Moreover, MI seems to rely on a network involving motor related regions including fronto-parietal areas and subcortical structures, supporting the view that MI and motor execution are very similar processes (Hétu et al., 2013). Additionally, extensive research has found motor imagery deficits in other common disorders such as spastic hemiplegia (Williams, Anderson, Reddihough, Reid, Vijayakumar, & Wilson, 2011), attention-deficit-hyperactivity-disorder (Lewis, Vance, Maruff, & Wilson, 2008; Williams, Omizzolo, Galea, & Vance, 2013), and cerebral palsy (Mutsaarts, Steenbergen, & Bekkering, 2007).

Children with DCD experience problems with tasks thought to rely on an internal model of movements such as MI, action planning and rapid online control of movements (Adams et al., 2014). Therefore, MI ability is thought to be reflective of one's ability to accurately form internal models of motor control (Skoura, Papaxanthis, Vinter, & Pozzo, 2005) and there is a deficit in MI ability for children with DCD. Internal models provide stability to the motor system by predicting the outcome of movements before sensorimotor feedback is available. Adams et al. (2016) showed that children with DCD are able to use MI, however; they are slower and less accurate than their typically developing (TD) peers. They also have an impaired ability, when compared to TD children, to produce familiar gestures, dependent on the type of gesture and presentation modality (Sinani et al., 2011). Additionally, two systematic reviews revealed that predictive control of movements is linked specifically to underlying deficits in motor control and learning, such as what is seen in DCD (Adams et al., 2014; Wilson et al., 2013).

Most studies of MI in children with DCD have employed two main paradigms: mental rotation and mental chronometry. A commonly used task for mental rotation is the hand rotation task (Adams et al., 2017a), in which laterality judgments of limb stimuli are made (*e.g.*, left and right hands) based on a display of different angles of rotations, and from different viewpoints (*e.g.,* back vs. palm view). For mental chronometry (Dahm & Rieger, 2016), evidence of a MI deficit is taken by comparing the durations of imagined and executed movements. In mental rotation tasks, MI performance in children with DCD has been shown to be slower and less accurate when compared to control groups (Deconinck et al., 2009). However, O'Shea & Moran (2017) raised caution to the use of mental chronometry paradigms as they offer information on the timing of MI but no information on MI accuracy.

However, little research has been conducted to explore MI ability in children with DCD through the use of questionnaires. According to Morris et al. (2005), MI ability is a multidimensional construct, that can be assessed in terms of factors such as controllability, vividness, and maintenance. Here, we used two questionnaires that assess MI through an individual's accuracy and vividness. A questionnaire measuring MI accuracy asks questions that have "correct" and "incorrect" answers. For example, with the Florida Praxis Imagery Questionnaire (FPIQ, Ochipa et al., 1997), participants are presented with the image of objects and asked to spatially manipulate the objects, and have to choose, from a set of alternatives, the object that would be in the correct orientation following manipulation. Questionnaires that measure MI vividness, on the other hand, rely on the self-report or perception of an individual's ability to imagine movements. The Movement Imagery Questionnaire for Children (MIQ-c, Martini, Carter, Yoxon, Cumming, & Ste-Marie, 2016) is in this category, as it asks participants to physically perform a task and then visualize the same task either through internal, external or kinesthetic imagery. Then they are asked to rate the difficulty of visualizing that movement on a 7-point likert scale (1 is very hard and 7 is very easy).

To date, only one study explored the components of MI ability in children with DCD through the use of questionnaires (Chang & Yu, 2016). Chang and Yu measured MI ability through a modified version of the FPIQ (adapted to be suitable for use in Taiwan) and aimed to understand characteristics of MI ability in children with varying levels of motor difficulty. The authors suggested that children with DCD did not consistently exhibit deficits in MI. These results were not entirely in line with previous results from Wilson et al. (2001) and further support the need to explore the components of MI through questionnaires. Implementing questionnaires to assess MI ability is appealing because: 1) They are relatively easy to administer to multiple participants at once 2) They require lower levels of training for administration, and 3) Minimal amount of resources are needed when compared to the other paradigms, such as the hand rotation task.

Therefore, the purpose of this study was to (1) compare MI ability between TD children and children with DCD, and to (2) investigate potential differences between MI accuracy and vividness within these groups. It is expected that TD children will show higher accuracy with their MI than children with DCD (Deconinck, Spitaels, Fias, & Lenoir, 2009; Williams, Omizzolo, Galea, & Vance, 2013). Additionally, we predicted that children with DCD would have higher MI vividness scores when compared to MI accuracy, due to the perceptual nature of the MIQ-c questionnaire.

2. Methods

2.1 Participants

A total of 101 children ranging from 7 to 12 years of age (*M* age = 9.97, *SD* = 1.71) from a large metropolitan area in North Texas were recruited for this study. None of the children had any known comorbidities (such as Attention-Deficit/Hyperactivity Disorder (ADHD); Autism Spectrum Disorder (ASD); Dyslexia, etc). Cognitive testing was conducted on all children and eight participants were excluded from the sample due to their performance on the Kaufmann Brief Intelligence Test - 2 (KBIT-2; Kaufmann & Kaufmann, 2004), with IQ composite scores either at the lower extreme or below average (14th percentile). After this exclusion, a total of 93 children remained in the study, with 42 children categorized with DCD (23 boys, 19 girls*; M* age = 9.81, *SD* = 1.73) and 51 TD children (26 boys, 25 girls*; M* age = 10.11, *SD* = 1.79).

We categorized children in the DCD group if they met the criterion A defined by the Diagnostic and Statistical Manual of Mental Disorders – 5th edition (DSM-5; American Psychiatric Association, 2013). The confirmation of criterion A (motor skills below age level given opportunities for learning) was based on scores on the red and amber zone of the Movement Assessment Battery for Children, 2nd edition (MABC-2; Henderson, Sugden & Barnett, 2007) and criterion D (motor difficulties are not explained by other conditions) were confirmed through the parents, whom stated that none of the children had any diagnoses. We wish to note that both criteria B (motor difficulties interfere with activities) and C (early onset of difficulties) were not formally tested. All children in the TD group scored on the green zone of the MABC-2.

The experimental protocol was approved by the Institutional Review Board (IRB) for the ethical treatment of human subjects. Children and parents were informed of the experimental procedures before participating in the study, parents signed the consent form, and children provided verbal consent as well as signed assent forms.

2.2 Measurements

2.2.1 *Cognitive ability*

Cognitive ability was measured using the *Kaufman Brief Intelligence Test*, 2nd edition (KBIT-2, Kaufman & Kaufman, 2004). The KBIT-2 is a brief and individually administered measure of verbal and nonverbal intelligence, with three components: IQ composite, verbal, and nonverbal. Kaufman and Kaufman (2004) recommend the KBIT-2 to be used as a screener for intellectual abilities. The KBIT-2 has been shown to have high reliability scores for the verbal scale (.91) and the IQ composite (.93). For the nonverbal scale, split-half reliability coefficients are in the .80s and .90s (Bain & Jaspers, 2004). In addition, performance on the KBIT-2 has been shown to have good convergent validity with longer, widely used measures of intellectual functioning (Kaufman & Kaufman, 2006). In the current study, the IQ composite score was used to measure overall cognitive ability for exclusion purposes.

2.2.2 *Motor ability*

Motor ability was measured using the *Movement Assessment Battery for Children – 2nd edition (MABC-2*, Henderson, Sugden & Barnett, 2007). The MABC-2 is a standardized assessment tool that requires a child to perform motor tasks to measure potential motor impairment in children aged 3 years to 16 years. The assessment is divided in three age bands: Age Band 1: 3-6 years, Age Band 2: 7-10 years and Age Band 3: 11-16 years, here, we used age bands 2 and 3. Within each age band, there are eight tasks grouped under three subscales: manual dexterity, aiming and catching, and balance. The MABC-2 typically takes anywhere between 20-40 minutes to be completed, depending on the age of the child. Once all tasks are completed, each child's individual scores are converted to standardized scores and then mapped onto a 'traffic light' system, that shows whether or not the child falls into the normal range (green), 'at risk' category requiring further monitoring (amber) or is highly likely to have a more serious movement problem (red). Henderson et al. (2007) provided evidence suggesting favorable psychometric properties for the MABC-2, with a reliability coefficient of .80 for the total test score and coefficients ranging from .73 to .84 for the individual component scores.

2.2.3 *MI accuracy*

MI accuracy was measured using the *Florida Praxis Imagery Questionnaire* (FPIQ), first presented by Ochipa et al. (1997) and later modified for children by Wilson et al. (2001). This modification established that all items were appropriate to children aged between 7 and 10 years of age. The FPIQ is an assessment used to determine the accuracy of an individual to imagine motor actions. Additionally, it has only been used to detect impairments in MI ability, rather than individual differences (Maruff, Wilson, & Currie, 2003). It consists of four subscales (kinesthetic, position, action, and object); each designed to evaluate different aspects of tool and object use. The kinesthetic subscale requires the participant to imagine which joint moves the most or least during a given action. The position subscale involves imagining the spatial position of the hand in relation to either the object or body parts of the person completing the action. The action subscale involves imagining the motion of the limb when performing an action. Finally, the object subscale involves imagining the object, presented in the question, used in an action. Correct answers indicate that the participant is able to correctly imagine the action required to arrive at the answer. Responses for each subscale are scored on a range of 0-12 points (correct answers). Total scores are calculated by adding the total correct scores in each subscale and dividing by the total twelve questions, the total score is presented in a percentage form. In total, there are four separate scores that are reflective of the individual's MI accuracy through each subscale (kinesthetic, position, action, and object). The scores can range from 0% (did not answer any of the twelve questions correctly) up to 100% (answered all twelve of the questions correctly). This questionnaire is formatted in a way that the same imagery-based question is asked in different ways for each one of the subscales. For example, a general question for imagery would be "Imagine you are using a pair of scissors". In order to target the kinesthetic subscale, the question would be "which joint moves more, your shoulder or your wrist?", and "which is higher, your thumb or your index finger?" for the position subscale. To our understanding, no psychometric evaluation of the questionnaire has been attempted.

2.2.4 *MI vividness*

MI vividness was measured using the *Movement Imagery Questionnaire - Children* (MIQ-c, Martini, Carter, Yoxon, Cumming, & Ste-Marie, 2016). The MIQ-c was developed and validated for children between 7 and 12 years of age based off of the Movement Imagery Questionnaire – 3 (MIQ-3; Williams et al., 2012) to measure how vivid children's visual (internal [IVI], external [EVI]) and kinesthetic (KI) images are- it measures how easy or difficult it was to imagine themselves performing the task. Instructions are read to participants and pictures are used to help children understand the different types of imagery perspectives being tested and the rating scale employed. The questionnaire consists of twelve items and four simple movements (knee raise, arm movement, waist bend, and jump). For each item, participants first physically perform the movement and then imagine the movement using IVI, EVI, or KI. Then they rate the ease or difficulty of imagining each movement on a 7-point Likert scale, with 1 representing "very hard to see/feel" and 7 representing "very easy to see/feel". A total of 28 points for each imagery perspective is possible and final scores are calculated by taking the average score of each perspective. The maximum score possible is 7, while the minimum score is 1. The MIQ-c has demonstrated adequate internal reliability for kinesthetic ($\alpha = .85$), internal visual ($\alpha = .74, .78$), and external visual ($\alpha = .70, .83$) (Quinton, Cumming, Gray, Geeson, Cooper, Crowley, & Williams, 2014).

2.3 Procedures

All participants referred to the study were tested in the lab after school hours or on weekends. Complete testing lasted about 2 hours. First, every child was tested with the KBIT-2 and MABC-2, then with the MIQ-c and FPIQ. These assessments were presented in counterbalanced order to alternate assessments that could be more tiring for children, particularly children with DCD, and to maintain the interest of participants. All participants were allowed to take as many breaks as needed throughout the testing procedures.

2.4 Data analysis

Each measurement of MI ability yielded scores for each subscale. To establish differences in motor ability and lack of differences in cognitive ability between the groups, we conducted independent t-tests for scores on the MABC-2 and KBIT-2 IQ composite values. To compare differences between the groups for each assessment and in the subscales, two separate general linear model analyses were conducted: A 2 x 3 (Group [TD, DCD] x Subscales [internal visual imagery, external visual imagery, kinesthetic imagery]) for MI vividness and a 2 x 4 (Group [TD, DCD] x Subscales [position, object, kinesthetic, action]) for MI accuracy. As previously mentioned, MI accuracy was measured through the FPIQ questionnaire, and MI vividness was measured by using the MIQ-c. As appropriate, Tukey post-hoc analyses were performed. We also reported the eta squared, η2, for effect size in all pairwise comparisons. All analyses were conducted using SPSS Version 19.0 (SPSS Inc., Chicago, IL).

3. Results

3.1 Group characteristics

Table 1 provides a visual representation of the mean differences in each group. TD children had significantly higher motor ability ($M = 49.04$, $SD = 17.43$) than children with DCD ($M = 9.59$, $SD = 5.58$); $t(91) = -14.08$, $p = 0.00$. No significant differences were found for cognitive ability, $t(91) = -1.22$, $p = .22$, TD: $M = 69.30$, $SD = 21.16$, DCD: $M = 63.89$, $SD = 21.34$.

[Insert Table 1 about here]

3.2 MI accuracy

Figure 1 and Table 1 provide a visual representation of the results for MI accuracy. Results indicated a significant effect for group, $F(1,91) = 4.59$, $p = .04$, $\eta^2 = 0.048$ and subscale, $F(3,273) = 40.78$, $p = .00$, $\eta^2 = 0.309$, but the interaction between Group x Subscale was not significant, $F(3,273) = .54$, $p = .66$, $\eta^2 = 0.006$. Post hoc analysis of the subscales showed significant differences between all subscales except for the comparison between position and object, with higher scores for action followed by position, object and kinesthetic.

[Insert Figure 1 about here]

3.3 MI vividness

Figure 2 and Table 1 provide a visual representation of the results for MI vividness. Results indicated no significant difference for group, $F(1,91) = 1.71, p = .20, \eta^2 = 0.019$, but did indicate a significant difference for subscale $F(2,182) = 11.67, p = .00, \eta^2 = 0.114$. The interaction between Group x Condition was not significant, $F(2,182) = .26, p = .78, \eta^2 = 0.003$. Post hoc analysis of the subscales showed significant differences between all subscales except for the comparison between IVI and EVI, with lower values for KI.

[Insert Figure 2 about here]

4. Discussion

The purpose of this study was to compare MI accuracy and vividness between children with and without DCD. Our results indicated that TD children were significantly more accurate in MI when compared to children with DCD, but no differences were found between groups on MI vividness. These findings confirmed our expectations. It was expected that TD children would be more accurate with their MI than children with DCD (Deconinck, Spitaels, Fias, & Lenoir, 2009; Williams, Omizzolo, Galea, & Vance, 2013). However, we also predicted that children with DCD would have similar MI vividness when compared to TD children, due to the perceptual nature of the MIQ-c questionnaire. When we explored differences in the subscales of MI accuracy, results indicated that the action values were significantly higher than both the object and position subscales, followed by the kinesthetic subscale, which had lower values overall. When looking at MI vividness, our findings showed that the KI subscale had lower values compared to both the IVI and EVI subscales.

While our results confirmed our expectations, we believe that the difference we found in MI accuracy can advance the understanding of MI deficit in this population. In general, these findings are aligned with previous studies showing that MI is less accurate in children with DCD

(Hyde & Wilson, 2013; Deconinck et al., 2009; Williams et al., 2008). It appears that children with DCD have significant problems in the conception and mastery of MI accuracy, which could be the one of the mechanisms associated with low motor coordination in this population. MI accuracy, as measured by the FPIQ, involves determining the general ability of an individual to imagine motor actions. In other words, it requires the child to rely on their actual motor ability to make decisions on action representation; and their ability will allow them to imagine the correct action. Because children with DCD have low motor performance, their ability to imagine actions to make correct decisions is also impaired.

Additionally, we were able to find significant differences in subscales for MI accuracy. Our results showed lower scores overall for the kinesthetic subscale, *M* = 62.41, *SD* = 12.20. According to Féry (2003), kinesthetic imagery seems particularly important in the development of motor skills, because kinesthetic imagery involves the sensations of how it feels to perform a task, including the effort and forces perceived during movement (Jeannerod, 1994). According to the imagery literature, it has been shown that kinesthetic imagery is regarded as the most difficult perspective of imagery (Hall & Martin, 1997; Wilson et al., 2001; Chang & Yu, 2016; Martini et al., 2016). Chang & Yu (2016), only observed significant differences in the kinesthetic subscale of the FPIQ (TD children; *M* = 5.4, *SD* = 1.4, children with DCD; *M* = 4.8, SD = 1.4. We do wish to note that these authors scored the FPIQ different than the protocol from previous research (that we used). These results add to the literature by establishing that kinesthetic imagery, as compared to position, object, and action imagery, is the most difficult to imagine for children, regardless of the presence of DCD.

Our lack of differences in MI vividness seems to be related to the nature of the MIQ-c, which explores the vividness of the child's visual and kinesthetic images. It does not require for the child to be accurate in their MI, but simply to imagine the motor skills. It appears that children with DCD may be aware enough of their motor difficulties, so that their MI vividness is representative of their motor ability. This can explain why significant differences were found with MI accuracy and not MI vividness. This is similar to what happens with the mental chronometry task - as long as a child's imagined ability (MI) is comparable to their real motor ability, then their performance will be optimal (regardless of whether their motor ability was high or low for that task). For example, in a motor task such as walking, if one child walks a specific distance in two minutes and then completes that same task using MI in two minutes, the similarities of the two performances denote a very vivid MI ability (if a child completed the same walking task in thirty seconds and imagined that same task to take thirty seconds using MI, that would also be a "high" MI vividness).

When looking at the subscales for MI vividness, our results were similar to the results found in MI accuracy, in which KI was perceived as the most difficult perspective to imagine. In the MIQ-c, KI requires the child to focus on the feeling of the movement rather than the perspective: internal (first person) and external (third person). The KI subscale was significantly lower than both the IVI and EVI, regardless of motor ability (*M* = 5.07, *SD* = 1.24). Martini et al. (2016) found similar results in that the KI subscale was lower than both EVI and IVI, with the values for the subscales being: EVI; *M* = 5.69, *SD* = 0.99, IVI; *M* = 5.17, *SD* = 1.03, KI; *M* = 4.78, *SD* = 1.07. Hétu et al. (2013) support that the notion that KI is more difficult to imagine since they noted that KI involves a more extensive neural network as important clusters of activation were observed than visual MI. These results help further expand the literature in that regardless of the modality of MI, kinesthetic imagery is still considered the most difficult to imagine for children, regardless of the presence of DCD, and perhaps should require more focus and time spent on developing this MI modality.

We believe that our data can contribute somewhat to the notion that there is a developmental delay in children with DCD as it relates to MI, as opposed to a fundamental difference. In other words, that means that children with DCD function at a lower age-related level with MI. Support for the developmental delay notion comes from Adams et al. (2017c), which showed that children with DCD can improve their MI skills over time suggesting that they can catch up to their TD peers. While several previous studies have also supported this delay (Hyde et al., 2014, Ruddock et al., 2016, Hyde & Wilson, 2013 & Fuelscher et al., 2015), the authors acknowledge that future studies are warranted. Here, we evaluated a different perspective of MI – our measures were indirect (questionnaire-based), but evaluated two different perspectives for MI. While vividness is related to perception of MI and it is highly dependent on an individual's ability to imagine (or perhaps even confidence to do so), accuracy as measured by the FPIQ has a clear right (and wrong) outcome. If we consider vividness an "easier", and perhaps more primary form of MI, we can establish that children with DCD have got the ability to use it, but are still working to develop accuracy of MI.

Another relevant discussion is how MI ability relates to measurements of MI. Further exploration on different measurements of MI can significantly aid in the understanding of the causes of MI deficit as well as how to rehabilitate aspects of motor difficulties. Here, we found that the measurement of MI, accuracy or vividness, as well as the use of questionnaires, is relevant in the discussion of the MI deficit associated with DCD. Additionally, the developmental aspects of MI ability should be explored to include adolescents and young adults in this population, to address potential changes in this ability. The direct application of these findings could be supported through MI training in children with DCD. Two previous studies show potential of MI training in children (Adams et al., 2017b; Wilson et al., 2016; Doussoulin & Rehbein, 2011). When considering MI training, it is important to consider the complexity of movement required, the perspective (IVI, EVI, KI), and the type of instruction provided (explicit vs. implicit).

While it is believed that this study is the first to compare MI accuracy and MI vividness in children with and without DCD through questionnaires, it is obvious that it presents limitations. One limitation is the fact that we did not measure executive function, and it is known that executive function can influence MI ability. It is also possible that there was not enough need for executive function within the MIQ-c, in order to show the MI deficit in children with DCD. MI deficits appear to be more pronounced in individuals with DCD as task complexity increases (Caçola, Gabbard, Ibana, & Romero, 2014), so the less complex tasks might not have been sufficient enough to elicit motor planning deficits and could possibly explain the lack of differences found between children with DCD and TD children in MI vividness. Furthermore, the tasks required in the MIQ-c are not as complex as those in the MABC-2. An example of a movement that is required in the MABC-2 (age-band 2) is the one-board balance task. This task requires the child to stand on one leg while balancing on a thin balance beam. The beam must not tilt so that a side touches the floor and the score is related to the amount of time spent balanced (not greater than 30 seconds). When comparing that task to a task presented in the MIQ-c, such as lifting one knee as high as you can and then slowly lower your leg, it becomes apparent that there is a difference in complexity of tasks. This further highlights the importance of exploring more complex motor skills for measurements of MI ability. Even with these concerns over the complexity of tasks required, we would like to point out that the MIQ-c demonstrated adequate internal reliability (Quinton et al., 2014) while also being developed and validated for children aged 7-12 years (Martini et al., 2016).

In conclusion, our findings indicate that the MI deficit seen in children with DCD is associated with MI accuracy, rather than MI vividness. More specifically, TD children were significantly more accurate than those with DCD, while there were no significant differences between the two groups for MI vividness. Furthermore, the kinesthetic subscale of both MI accuracy and MI vividness was scored lowest than all other subscales. These results add to the current research supporting that children with DCD have MI deficits and extends that these deficits are found only in MI accuracy and not MI vividness. These results suggest the need of further exploration into specific measurements of MI in children with DCD.

Table 1

Group characteristics of participants included in the study and effect sizes for pairwise DCD-TD comparisons.

	TD		DCD		
Variable	M	SD	M	SD	Effect size (η^2)
MABC-2	49.04	17.43	9.59	5.58	.828
KBIT-2	69.29	21.15	63.88	21.33	.126
MI accuracy					
Kinesthetic	63.76	11.40	60.76	13.04	.122
Position	76.71	13.42	73.50	14.02	.118
Action	84.73	11.42	78.33	13.37	.253
Object	72.43	12.23	70.21	17.97	.071
MI vividness					
Internal	5.50	1.06	5.27	1.21	.105
External	5.69	0.87	5.51	1.17	.089
Kinesthetic	5.23	1.09	4.88	1.38	.138

Note. MABC-2- Movement Assessment Battery for Children; KBIT-2- Kauffman Brief Intelligence Test; TD - Typically Developing; DCD - Developmental Coordination Disorder; MI accuracy as measured by the Florida Praxis Imagery Questionnaire (FPIQ); MI vividness as measured by the Movement Imagery Questionnaire for Children.

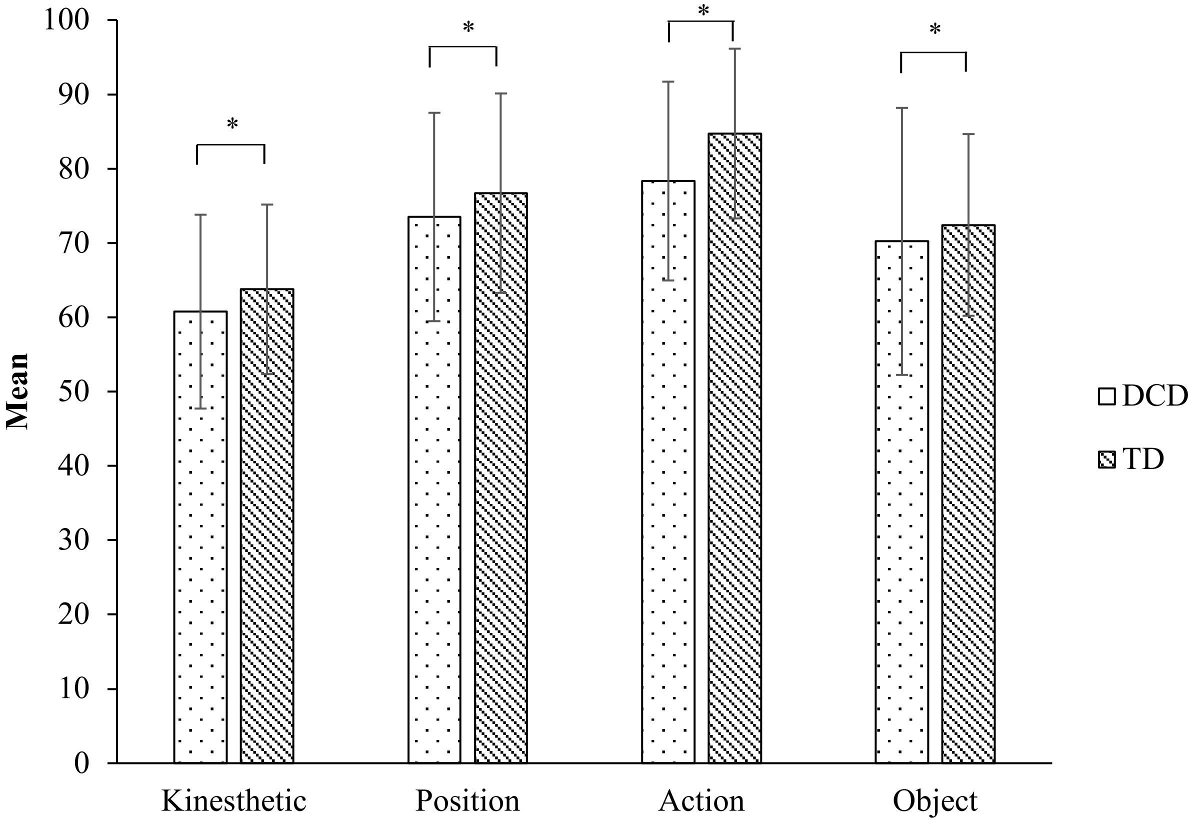

Figure 1. Mean and standard deviation for MI accuracy in children with DCD and TD children. *Note.* Range of scores for FPIQ can be 0 (answered all questions incorrectly) to 100 (answered all questions correctly).

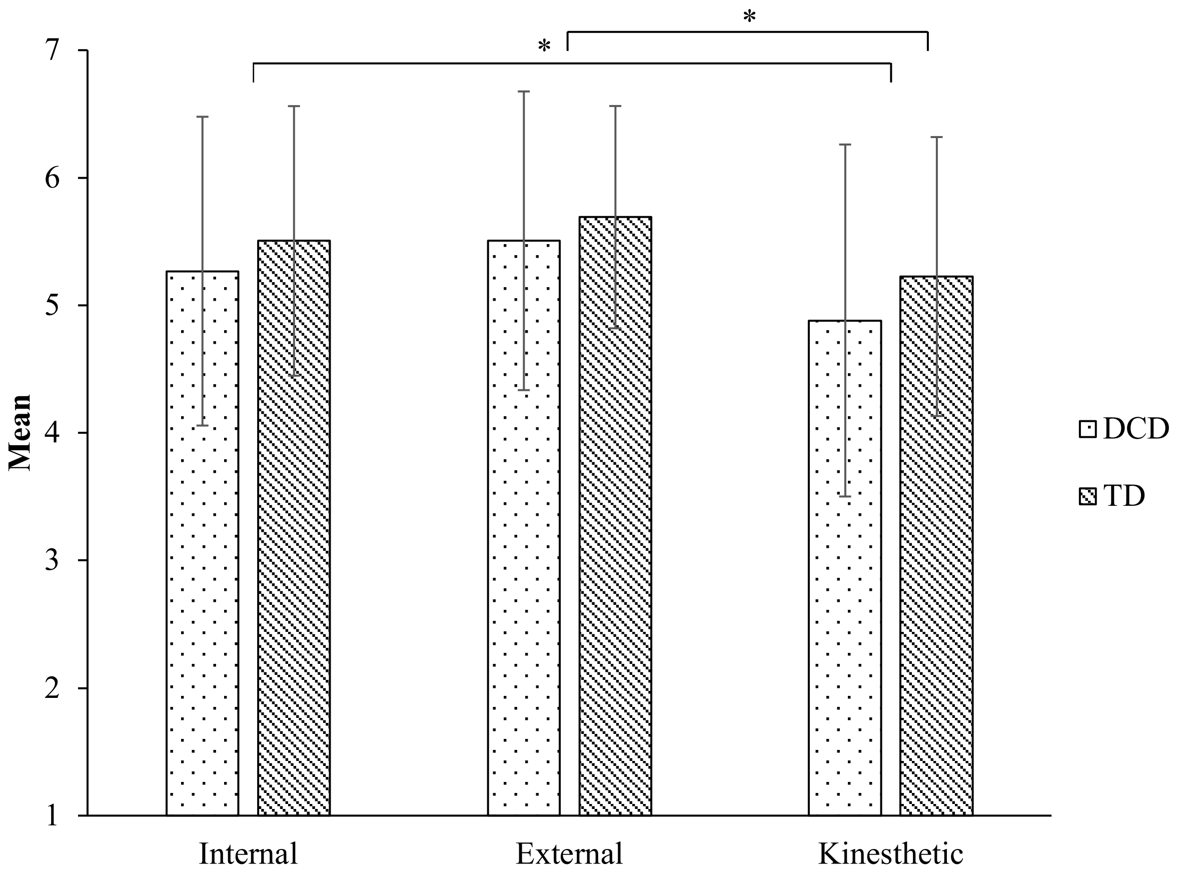

Figure 2. Mean and standard deviation for MI vividness ability in children with DCD and TD children. *Note.* Range of scores for MIQ-c can be 1 (very hard) to 7 (very easy).

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Chapter 4

Future Directions

In review, the two studies completed for this dissertation provided further insight into the development of MI ability and the association between MI ability and motor proficiency. Study 1 investigated age-related differences in MI accuracy and vividness and the association of motor proficiency While study 2 investigated the association between MI accuracy and vividness and motor deficits. The direct application of these studies will help with the further understanding of the development of MI ability into adulthood which can improve how individuals create and implement MI training protocols, which can help better our ability to predict performance enhancements for individuals with motor deficits caused by disorders or those who have experienced motor impairment due to aging. Ultimately, this could potentially improve motor skill interventions

The purpose of the first study was to compare MI accuracy and vividness between children and young adults while also exploring the role of motor proficiency on MI. These results indicated that young adults were significantly more accurate and rate their MI significantly more vivid across all subscales in MI ability when compared to children. These findings confirmed expectations that young adults would display significantly higher MI accuracy and vividness than children. Additionally, results indicated that the action subscale for MI accuracy significantly predicted motor proficiency. These results indicate that MI accuracy and MI vividness continue to develop into young adulthood. This supports further investigation into the impact of motor skill interventions on the development of MI, the unique nature of MI accuracy and vividness, and the potential relationship between measures of MI ability and motor proficiency.

The purpose of the second study was to compare MI accuracy and vividness between children with and without DCD. Results indicated that typically developing children were significantly more accuracy in MI when compared to children with DCD, but no differences were found between groups on MI vividness. we believe that the difference we found in MI accuracy can advance the understanding of MI deficit in this population. In general, these findings are aligned with previous studies showing that MI is less accurate in children with DCD (Hyde & Wilson, 2013; Deconinck et al., 2009; Williams et al., 2008). It appears that children with DCD have significant problems in the conception and mastery of MI accuracy, which could be the one of the mechanisms associated with low motor coordination in this population. This supports further investigation in to MI accuracy and how the subscales independently interact with MI development in children with motor deficits.

The natural continuation of this line of research is to further explore the development of MI throughout the lifespan. To date, there has been no study exploring the developmental differences of MI accuracy and vividness through young adults into middle-aged and older adults. Better understanding these differences can provide valuable insight into the general nature of MI ability which in turn can help further our ability to improve motor proficiency through MI training in an aging population.

Furthermore, one could argue that there is a significant concern regarding the lack validity reported for the FPIQ. While the FPIQ has been used recently in published research involving children and adolescents and has found significant differences (Wilson, Maruff, Ives, & Currie, 2001; Choudhury, Charman, Bird, & Blakemore, 2007; Lust, Wilson, & Steenbergen, 2014; Fuchs & Caçola, 2016) we acknowledge the need for a validation study. Conducting this type of study would help to develop a more thorough understanding of the components and characteristics of MI accuracy (the subscales). Additionally, within this warranted validation study, a modification of the FPIQ may be warranted. The current version of the FPIQ was first developed by Ochipa et al. (1997) and later modified for children by Wilson et al. (2001). This modification established that all items were appropriate to children aged between 7 and 10 years of age. However, this was conducted using common terminology found in Australia and may create confusion for individuals living in North America. Modifying this questionnaire to include common North American terminology and incorporates similar general motor skills commonly assessed in motor proficiency assessments would provide an appropriate questionnaire to measure MI accuracy. Not only would this would create an opportunity to provide psychometric evaluation of this questionnaire, it would also allow for us to gain better insight into the association between MI accuracy and motor proficiency.

In conclusion, this dissertation showed that children with DCD have MI deficits and further extends that these deficits are found only in MI accuracy and not MI vividness. Furthermore, young adults are significantly more accurate and vivid across all subscales of MI ability when compared to children. This indicates that MI accuracy and vividness continue to develop into young adulthood and that there are unique differences within the components of MI accuracy. One way to look at this is the deficits associated with disorders affecting motor ability (such as DCD) are also found within MI ability. Furthermore, while improvement occurs from children to young adults, it appears that individual dimensions on MI ability (kinesthetic, position, action and object) and perspectives (internal, external and kinesthetic) develop differently within individuals.