The Relationship Between Movement Imagery and Online Control in Typically Developing Children

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Abstract

The ability to mentally represent actions is suggested to have a role in the online control of movement in healthy adults. Children's movement imagery ability and online control have been shown to develop at similar non-linear rates. The current study investigated the relationship between movement imagery and online control in children by comparing implicit and explicit movement imagery measures with the ability to make online trajectory corrections. Imagery ability was a significant predictor of children's online control of reaching once age and general reaching efficiency were controlled for. These findings extend the proposed relationship between movement imagery and online control.

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Chapter 1: Literature Review

The ability of the motor system to adapt to unexpected environmental changes is essential for maintaining accuracy during goal directed actions. This process requires the integration of incoming sensory information with the desired trajectory, allowing for discrepancies to be corrected. However, the process of integrating incoming sensory information with current limb position, production of an error signal, and initiation of a corrective movement is associated with delays (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). Given the associated delays that occur due to these basic neural factors, one would assume that for rapid aiming movements, the incoming sensory information is integrated and incorporated into movement too late to be useful for trajectory correction as limb position will have changed substantially. Interestingly, this is not the case. The current theories of online control suggest that the incoming sensory information is compared to a mental representation of the action that incorporates predicted sensory information in order to overcome the aforementioned sensory delays (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). These mental action representations are termed efference copies, while the process of using this efference copy to predict sensory information is termed feedforward modeling (Desmurget & Grafton, 2000; Jordan & Rumelhart, 1992; Wolpert & Miall, 1996; Wolpert & Ghahramani, 2000; Wolpert, Diedrichsen, & Flanagan, 2011). This process allows individuals to correct trajectories during rapid goal directed reaches (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). One technique for measuring the ability to make these corrections, termed online control, is a double-step reaching task (DSRT) (Cressman, Franks, Enns, & Chua, 2006; Desmurget et al., 1999; Goodale, Pelisson, &

Prablanc, 1986; Hyde, et al., 2013; Pisella et al., 2000; Plumb et al., 2008). While this task allows researchers to quantify the ability to adapt to changes in the environment, it fails to directly access the ability to generate a mental representation of that movement.

Movement imagery (MI) is described as the ability of an individual to mentally perform an action in the absence of overt movement (Decety, 1996). This form of mentally representing an action is believed to allow researchers access to the mental representations associated with real movements, as it is proposed to incorporate temporal, biomechanical, and force production constraints also observed in executed actions (Jeannerod, 2006; McAvinue & Robertson, 2008; Munzert, Lorey, & Zentgraf, 2009; Munzert & Zentgraf, 2009). While an individual can be specifically instructed to utilize movement imagery, termed explicit movement imagery, it is also possible to induce movement imagery unconsciously to perform a task, termed implicit movement imagery. These differences have led to various measures of movement imagery ability, including; mental chronometry (McAvinue & Robertson, 2008) and self-report questionnaires (Hall, Pongrac, & Buckloz, 1983; Isaac, Marks, & Russell, 1986; Roberts et al., 2008; Martini, Carter, Yoxon, Cumming, & Ste-Marie, 2016). Self-report questionnaires allow for a more detailed look into movement imagery ability as they allow for the separation of the three movement imagery perspectives, which have allowed researchers to determine that certain perspectives are more beneficial in specific situations or tasks (White & Hardy, 1995; Williams et al., 2012). These measures of movement imagery have opened up several possibilities for potentially studying the association between this process and the action representations involved in online control.

The Motor System: How do we complete a goal directed movement?

It is suggested that goal directed reaching movements involve the creation and implementation of a motor plan (Desmurget & Grafton, 2000, Wolpert & Ghahramani, 2000). Once the motor plan has been initiated it is important to have some mechanism of error detection in order to account for either errors in movement execution or a change in the environment in which the movement takes place. Thus, in order to understand the ability to control goal directed reaching movements in-flight, we must first understand these components.

Motor Planning

A motor plan is selected based on the requirements of the task, as well as the current state of the system (Desmurget & Grafton, 2000) and is proposed to include constraints based on speed, accuracy and energy cost (Elliott, Hansen, Mendoza, & Tremblay, 2004; Elliott, Hansen, & Grierson, 2009). The brain can then select the appropriate motor plan to complete the given task by integrating these constraints. Although there are nearly infinite possible movement trajectories to complete any one goal directed reach, individuals tend to select similar movements. It is suggested that this movement selection is based on minimizing the possible error associated with a particular movement pattern (Harris & Wolpert, 1998). Every movement pattern, if repeated an infinite number of times, will have the same average end-point across trials. Where they differ however, is on the variance around this average endpoint (Wolpert & Ghahramani, 2000). In order to minimize potential for error, the selected movement is one that has the least end-point variability, while adhering to the aforementioned constraints of the task. It is suggested that the variability observed is a result of noise associated with the amount of neural signals required to complete this movement (Wolpert & Ghahramani, 2000).

Smooth movements, movements with smooth velocity profiles, require less motor commands than jerky movements, thus generating less noise and less variability (Wolpert & Ghahramani, 2000). Once the correct motor plan is selected Wolpert & Ghahramani, 2000, suggest that the brain creates a copy of this movement and the predicted sensory outcomes. This copy is a mental representation of the planned movement, also termed an efference copy (Andersen, & Cui, 2009).

Internal Models and Error Detection

The ability to form an efference copy of a movement is suggest to allow the central nervous system (CNS) to transform sensory signals into a motor command (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). This transformation requires that the CNS model the transformation prior to being able to implement it into a physical movement. The potential models used by the CNS are termed internal models, as they do not involve any overt movement production. It has been suggested that there are two types of internal models: feedback or feedforward models (Osu, Morishige, Miyamoto, & Kawato, 2009; Wolpert & Ghahramani, 2000). While both models are used, these two suggested models allow for fine-tuning movements. To understand these models it is necessary to have a general understanding of movement production and error detection.

In the process of performing a goal directed reaching movement, errors can occur due to both signal noise, nonsense neural activity associated with the intended signal due to the variability of excitability of a neuron (Ferster, 1996), and environmental factors, such as target perturbation or varying fluid densities, for example underwater or in the air. This could lead an individual to plan and execute the incorrect movement for a particular environment. To correct for these errors, one must first recognize that an error has occurred. Errors are identified through the sensory system (Desmurget & Grafton, 2000; Glover, 2004; Wolpert & Ghahramani, 2000). Sensory signals such as visual or kinesthetic information provide information on limb position in space (Glover, 2004). This information is used to determine the current state of the system (for goal directed reaches, including limb position and target location) (Desmurget & Grafton, 2000; Glover, 2004; Wolpert & Ghahramani, 2000). This information is then integrated with the desired limb displacement so as to create an inverse model of the action which is used to estimate the correct motor command required to produce the desired displacement (Desmurget & Grafton, 2000). Once a motor plan is selected, the individual may initiate the movement, during which time sensory signals of the current state of the system (e.g. current limb position/velocity and target location) is compared to the desired trajectory in real time (Wolpert & Ghahramani, 2000). If a discrepancy exists, an error signal will be generated and corrections will be made. While slower movements allow ample time for sensory information to be integrated allowing for corrective movements to be incorporated, for faster movements, sensory signals are too slow to be useful to recognize and correct errors in real time. For example using only visual sensory information to estimate position would have an approximate delay of 100ms before it could be integrated within the motor plan leading to error detection (Wolpert & Ghahramani, 2000) and subsequently incorporated to produce a corrective muscle contraction. For example if the correction required a biceps contraction, the delay between contraction and actual movement of the biceps is approximately 100-150ms (Biguer, Jeannerod, & Prablanc, 1982; Godaux, Koulischer, & Jacquy, 1992). Furthermore, in rapid reaching movements, these delays allow time during which further errors could occur and different corrections would need to be made. As such, to bypass these sensory delays it was suggested that humans use a feedforward control models whereby the efference copy is used to predict expected sensory feedback to estimate the current state of the system (Desmurget & Grafton, 2000; Glover, 2004; Wolpert & Ghahramani, 2000). In feedforward models, the current sensory information is compared to the predicted sensory information and state so as to detect errors, whereas in feedback control models incoming sensory signals are compared with the previously known state of the system (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). It is suggested that a more detailed and accurate efference copy will have a more accurate prediction of sensory information, and therefore produce a more accurate adjustment (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). This ability to adjust to differences between the efference copy and incoming sensory information is the basis upon which online control measures have been created.

Measuring Online Control

To measure the ability of an individual to make trajectory corrections during rapid aiming movements, an error must exist in the original trajectory. There are several ways to create an error signal, each of which involves creating discrepancies between the movement plan and the actual movement. One common method is to change the target location at movement onset. This is the basis for the DSRT, also termed jump trial task (Cressman et al., 2006; Desmurget et al., 1999; Goodale et al., 1986; Hyde et al., 2013; Pisella et al., 2000; Plumb et al., 2008). Generally, this task requires participants to complete a series of rapid reaching movements from a home position to a target. It is important that the individual be instructed to reach as quickly and accurately as possible in order to avoid the use of slower sensory feedback loops associated with longer movement times, which would not require the use of feedforward processing. While in the majority of trials (80-85% of trials), the appearing target will appear and remain stationary throughout the trial, during the other 15-20% of trials, the target will jump to areas located to either the left or the right of the original target location. The change in target position occurs either during an orienting saccade (i.e., the movement of the eyes toward the original target), which generally takes approximately 200ms (Biguer et al., 1982; Desmurget et al., 1999) or at movement onset (Hyde & Wilson, 2011; Ruddock et al., 2014; Wilson & Hyde, 2013). These trials, where the target ‘jumps’ to either side of the original target, are deemed the double step or jump trials (Goodale et al. 1986). In healthy individuals, the detection of the error leads to a smooth correction in their trajectory, allowing them to adapt to this new target location. In fact, trajectories during double step trials display similar movement times and single peak velocity profiles to those evidenced in pointing at a single stationary target (Goodale et al., 1986; Magescas, Urquizar, & Prablanc, 2009; Prablanc & Martin, 1992). Interestingly, these corrections occur even when vision of the reaching limb is not available, suggesting non-visual regulation of the movement (Desmurget et al., 2005; Goodale et al., 1986; Prablanc & Martin, 1992). Desmurget et al. (2005) also investigated the importance of continuous vision of the target in the absence of limb vision. A sensor attached to a participant’s fingertip was used to record hand position with targets displayed on an overlaid surface with a half reflective mirror allowing LED lights to be visible to the participant. Red LED lights served as the possible target locations along with a separate green LED light serving as the home base. Participants were also required to rest their head on a chin rest in order to control head movement and rely solely on saccadic eye movement. Targets appeared at any one of seven potential locations, each of which was at a fixed distance from the home base. Two conditions were tested, both of which allowed for saccadic eye movement however, in the first condition the target remained illuminated until the end of limb movement whereas in the second condition, the target was extinguished upon the initiation of the first saccade. Desmurget et al. (2005) observed that regardless of condition, hand movements are initiated prior to the completion of the first saccade. They also observed that the initial kinematics were identical in all movement conditions, and that the overall shape of the velocity curve remain similar irrespective of the degree of trajectory correction. These findings suggest that trajectory corrections do not rely solely on visual sensory information as, not only is limb vision unnecessary for online corrections, but neither is ongoing vision of the target location.

Evidence also suggests that conscious perception of target displacement is also not a requirement for online trajectory corrections (Goodale et al., 1986; Pisella, 2000). The fact that conscious perception is not necessary has led to the concept of automatic pilot of the hand in goal directed reaching (Cressman et al., 2006; McIntosh, Mulroue, & Brockmole, 2010; Pisella et al., 2000; Prablanc & Martin, 1992). This idea is further supported by Pisella et al. (2000), who demonstrated that when a target perturbation is associated with either a stop or a go condition, individuals made a significant amount of incorrect go corrections. That is to say, when a perturbation was associated with a stop signal, a significant amount of trials evidenced an inability discontinue the trajectory correction. This suggests that while the ability to inhibit the automatic response does exist, there is a discrepancy between motor response and decision-making processes (Gaveau et al., 2014).

In a DSRT, the primary measures of online control are the time to correction (TTC) (Cressman et al., 2010; Desmurget et al., 1999; Gaveau et al., 2014; Hyde et al., 2013) and the endpoint error (Gaveau et al. 2014, Goodale et al., 1986); either variable endpoint error (VE), which relates to the standard deviation of the endpoints, or constant endpoint error (CE), which measures the average displacement of the endpoint from the target. The VE and CE determine the accuracy of the corrected reach toward the target. The TTC corresponds to the point in the trajectory where the participant begins to deviate toward the new target location (Cressman et al., 2010; Desmurget et al., 1999; Gaveau et al., 2014; Goodale et al., 1986; Hyde et al., 2013). That is how long it takes the participant to begin correcting for the error.

There are several ways to determine the initial point of trajectory correction. The first method requires the generation of a mean path based on all of the non-jump trials, as well as the two standard deviation range of this path. Each individual jump trial is then compared to the mean path to determine at what point the current trial path intercepts the two standard limits. This indicates that a corrective movement has been initiated. Researchers then work backwards to visually identify the point where the trajectory originally adapted to this new path using position, velocity, and acceleration profiles (Hyde et al., 2013; Hyde & Wilson, 2013b; Pisella et al., 2000; Ruddock et al., 2014; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007).

The second method, described by Sarlegna (2006), involves determining the angular velocity at each recorded position in the jump trials. During a non-jump trial angular displacement will remain very small, as participants are reaching towards a central target, whereas jump trials will have a non-central target and thus, a greater angular velocity. The point of peak angular velocity occurs during the trajectory correction. This point is used, similar to the 2 standard deviation intercept, to work backwards in order to determine TTC. However, in this case the TTC point is defined as the point at which angular velocity decreases to less than 5°/s.

The third method involves the use of paired t-tests of the mean path to the mean perturbed path to determine TTC (Cressman, Cameron, Lam, Franks, & Chua, 2010). These tests are used between all points following the 100ms point, as no corrections occur prior to this point. Once a significant t-test is found, the test must remain significant for the next 35 time interval points in order to be determined as the TTC point.

A major advantage of the DSRT is that it has been validated as a measure of online control through extensive use with adults, children, and special populations (Desmurget et al., 1999; Goodale et al., 1986; Hyde et al., 2011; 2013; Hyde & Wilson, 2013; King, Oliveira, Contreras-Vidal, & Clark, 2012; Pisella et al., 2000; Sarlegna, 2006). While it is important to have a method of quantifying online control, it is also important to determine the associated brain structures in order to make findings useful in a clinical setting.

Error detection in the brain: The posterior parietal cortex

Recent studies have investigated the active brain regions associated with error detection and online control processes. Clower et al. (1996) used positron emission tomography (PET) to determine brain activation patterns associated with adaptations to a distorted visual field, created using prism goggles, during a goal directed reaching task.

The results of this study showed activation of the posterior parietal cortex (PPC) during online control of goal directed reaching movements. To further support the association between the PPC and online control, researchers attempted to disrupt online corrections by using transcranial magnetic stimulation (TMS) pulses on the PPC during a DSRT (Desmurget et al., 1999). In this study the TMS was applied following movement onset in both stationary and jump trials. In so doing, they observed disruptions in the ability to make trajectory corrections during jump trials in four out of five participants. In addition, end point variability increased in non-jump trials. These findings suggest that the PPC plays a significant role in the error detection associated with feedforward processes during goal directed reaching. Results in a similar study by Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher (2011) also support the notion that the PPC is involved in error detection as they found TMS pulses to the PPC led to delays in initiating the trajectory correction. This inability to make corrections following a shift in target location was also observed in a patient suffering from optic ataxia caused by a lesion of the intra-parietal sulcus of the PPC (Pisella et al., 2000). Wolpert, Miall, & Kawato (1998) also studied a patient with parietal lesions. In their study the participant was required to complete a grip task requiring the maintenance of a constant force output, a reaching accuracy task to targets in the periphery, and perception of limb location. Each task showed decrements compared to healthy subjects. However, these decrements were observed shortly after the onset of the trials. The authors suggested that these decrements were related to a rapidly decaying motor representation, which could lead to errors when incorporating information into a motor plan (Wolpert et al., 1998). The activation in the PPC was also evidenced in a tetraplegic participant during imagined movements (Aflalo, et al., 2015).

In combination these findings point to the PPC as the area in the brain where the motor representation is maintained and accessed in order to detect errors. Not only is this the case but the activation of the PPC even in the absence of movement suggests that accessing these mental representations through imagined actions is a viable method of investigating motor control processes.

Accessing Motor Representations

The Simulation Theory suggests that action involves both covert stages and overt stages along a continuum (Jeannerod, 2001). Covert action stages involve predicted states, and must include the goal of the action, the means to attain the goal, and predicted consequences (Jeannerod, 2001). The term covert suggests that these stages of movement cannot be observed. At the other end of the continuum is overt action, or movement execution. In this theory the overt stage always follows the covert stage, however, the overt stage is not a requirement for the covert stage. In fact, Jeannerod (2001) suggests that covert actions are in fact actions, except for the fact that they are not executed. This covert stage suggested by Jeannerod (2001) appears to mimic the idea of motor planning.

An alternative to the Simulation Theory is the Emulation Theory described by Grush (2004). The major difference between the two theories is that the Simulation Theory is founded on a motor plan being the basis of the covert action and so fails to account for the lack of proprioceptive and kinesthetic feedback, relayed from the Golgi apparatus and muscle spindles that are present in the overt action stages (Grush, 2004). Emulation Theory remedies this gap by suggesting that a covert movement requires the motor plan to be run through a body emulator, in order to generate faux proprioceptive and kinesthetic feedback (Grush, 2004).

Both of these theories involve generating a mental representation of the action requiring the generation of a motor plan. While measuring an individual's ability to plan an action is difficult, another form of covert action has been suggested to provide some insight into the motor representation (Grush, 2004; Jeannerod, 2001). This form of covert action is supported by both theories and has been termed movement imagery.

Movement Imagery

Movement imagery (MI) is the ability of an individual to mentally perform an action in the absence of overt movement (Decety, 1996). Current research illustrates that the same brain structures appear to be activated whether a movement is imagined or is actually produced (Jeannerod, 2001; Munzert et al., 2009). Not only are the same areas activated, but both imagined and actual movements are subject to the same biomechanical constraints (Jeannerod, 2006). For instance, imagined and actual movement times have been highly correlated. That is to say, imagined movement times reflect the biomechanical constraints associated with the actual movements. These findings indicate a strong association between MI and motor performance (Gabbard, 2009). MI has been described as providing information on a person's ability to generate motor representations (Jeannerod, 2001; McAvinue & Robertson, 2008). Although the ability to utilize MI develops in all individuals, there are differences in MI ability or quality. These differences have been associated with differences in motor performance (Gabbard & Bobbio, 2011; Gabbard, Cacola, & Bobbio, 2012; Hyde et al. 2013; Williams, Thomas, Maruff, & Wilson, 2008). For instance, poor ability to image movement has been noted in children suffering from Developmental Coordination Disorder (DCD), a condition that is manifested by poor motor coordination resulting in difficulty in daily tasks, as well as sports activities (Gabbard & Bobbio, 2011).

While imagery can involve many different sensory modalities, MI mostly involves visual and kinesthetic modalities (Hall et al., 1985). Visual imagery involves the participant seeing him or herself performing a specified action, while kinesthetic imagery involves the participant feeling himself performing the action (position and movement of body parts). Recently, the visual component of movement imagery has been further categorized in terms of perspective (Williams et al., 2012). One can observe an action from either the 1st person perspective or the 3rd person perspective. In a first person perspective, the person would see him or herself performing an action as if looking through his or her own eyes; whereas, in a 3rd person perspective, the person would see him or herself performing the action from an external view point, as though someone else was looking at him or her (like watching an action on television) (Williams et al., 2012). The 1st person and 3rd person viewpoints of movement imagery have been coined internal visual and external visual, respectively (White & Hardy, 1995). Depending on what is being imaged, it may be more beneficial to image from one perspective than another (Williams, et al., 2012). For example, White & Hardy (1995) found that using an external visual perspective led to better observation learning and retention of movements that rely heavily on form; whereas the use of an internal perspective was more beneficial for open skills involving precise timing and coordination, which rely more on perception. Their study compared performance of a gymnastics skill, performed with rhythmic gymnastics clubs, as well as a dry land slalom skill, performed in a wheel chair. The external visual perspective was associated with improved performance significantly more than the internal perspective for the gymnastics skill; however, for the slalom the internal visual perspective showed greater skill improvements. Similarly, Hardy & Callow (1999), observed a performance advantage following the use of external and internal imagery perspectives in both a gymnastics task and karate kata, both of which require proper form for success. These findings support the importance of studying imagery from different perspectives. As such, a measure of movement imagery ability needs to take into consideration the ability to image from these different perspectives.

Measuring Movement Imagery

Three different types of movement measures exist: mental chronometry, mental rotation, and self-report questionnaires (Heremans, Helsen, & Feys, 2008; McAvinue & Robertson, 2008). Mental chronometry and self-report questionnaires are known as explicit measures of movement imagery ability because they ask individuals to consciously imagine performing the movement (Jeannerod, 1994). In contrast, mental rotation is known as an implicit measure of movement imagery because subjects are asked to perform a particular task, with no reference to imagery (McAvinue & Robertson, 2008). In these tasks, it is assumed that the participant will use movement imagery to complete them.

Prospective judgment tasks are one type of task used to elicit and measure implicit movement imagery (McAvinue & Robertson, 2008). The most common stimulus currently used is the hand (De Lange, Helmich, & Toni, 2006; Gabbard, 2009; Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Hyde et al. 2013; Takeda, Shimoda, Sato, Ogano, & Kato,,2009). There are two types of prospective judgment tasks. The object of the first type (also known as mental rotation task) is to determine the laterality (e.g. right or left) of a given visual stimulus. Another example of a prospective judgment task is one that requires individuals to choose which image of a hand represents the hand position they would use to grasp a particular object or tool (McAvinue & Robertson, 2008). In both tasks, it is assumed that the participant used movement imagery to determine laterality or correct hand position. This type of task has been used extensively in the literature (De Lange et al., 2006; Gabbard, 2009; Ganis et al., 2000; Hyde et al. 2013; Takeda et al., 2009) to study movement imagery ability. In Hyde et al. (2013) the task required individuals to indicate, by pushing a button as quickly as possible, whether the rotated image of the hand was a left hand or a right hand. It was found that in these tasks response time (or reaction time) for the imagined hand movement corresponds to the same biomechanical constraints as actual hand movements. In other words, more awkward hand positions or angles of hand rotation have been shown to require greater time to make laterality judgments (Hyde et al., 2013, Parsons 1994). For example, in a hand rotation task, a 0° rotation (with the fingers directed upwards) elicits the shortest reaction time, which increases with increasing rotation of the stimulus (Hyde et al., 2013: Parsons, 1994; Takeda et al., 2009). To continue with the concept of awkward hand positions, it has also been shown that lateral rotations of the hand stimuli elicit longer reaction times than those of medially rotated stimuli. It has been suggested that this is due to the biomechanical constraints associated with wrist movements; the hand has less range of motion for lateral rotation than that of medial rotation (Hyde et al., 2013). In both implicit movement imagery tasks is presumed that the more quickly and accurately an individual can make these laterality judgments, the better their imagery ability.

Mental Chronometry

Mental chronometry measures involve the timing of imagined movements. This measure is based on the assumption that the time to mentally perform a task reflects the cognitive processes underlying that task (Jeannerod, 1997; McAvinue & Robertson, 2008). The task requires subjects to actually perform a task (e.g., walk different distances or reach for different targets of different sizes) or to imagine doing these same tasks. Researchers recorded the duration of each of these movements, both real and imagined. It is proposed that the closer the imaged time is to the actual time, the better the ability to image (McAvinue & Robertson, 2008).

For actual movements, an increase in task difficulty is associated with an increase in movement time. This relationship is termed Fitt's Law (McAvinue & Robertson, 2008). A Fitt's task, which involves a movement, with various degrees of difficulty, is an example of a task that utilizes mental chronometry (Decety, Jeannerod, & Prablanc, 1989; Decety 1991). For example, Decety (1991) had participants either walk, or image walking, across various widths of balance beams and timed both actions. Both real and imaged movement times were seen to increase as balance beam width decreased, suggesting that similar to real movements, imaged movements adhere to Fitt's Law. Decety & Jeannerod (1995) also evidenced movement imagery's adherence to Fitt's Law through the use of virtual reality. Participants wore a virtual reality helmet through which they were shown gates, which appeared to be located at 3m, 6m, and 9m. At these locations gates could also be one of three widths; 45cm, 90cm, 135cm. Participants were shown the gates for a 5s interval after which, the image was occluded. They were then required to imagine themselves walking through that gate. In accordance with Fitt's Law, Decety and Jeannerod (1995) observed that imagined movement time had a linear relationship with the index of difficulty of the task (i.e. width and distance of the gate). It is movement imagery's adherence to Fitt's Law that allows researchers to use mental chronometry during a Fitt's Task as an assessment of MI ability.

Self-report Questionnaires as Measures of Imagery Ability

Self-report questionnaires are currently a commonly used measure of assessing movement imagery ability for several reasons; they are cost effective, easy to administer, less time consuming than other techniques, such as mental chronometry, and allows one to tap into the different imagery modalities as well as different perspectives of movement imagery. Different movement imagery questionnaires exist. The two most widely used are the Vividness of Movement Imagery Questionnaire (VMIQ) developed by Isaac, Marks, and Russell (1986) and the Movement Imagey Questionnaire (Hall & Pongrac, 1983) The VMIQ was designed to evaluate both visual and kinesthetic aspects of movement imagery. Recently a revised VMIQ-2 was developed in order to separate the visual component of the VMIQ into external and internal visual perspectives (Roberts, Callow, Hardy, Markland, & Bringer, 2008). The VMIQ-2 is composed of 24 movements, spanning from basic walking to more complex movements, such as swinging on a rope. Individuals are instructed to first image someone else performing the movement, then image themselves performing the movement, and finally to image feeling themselves performing the movement. They must then rate the vividness with which they can image the movement on a 5-point likert scale, with 1 being, ‘‘Perfectly clear and as vivid as normal vision’’ and 5 being, ‘‘No image at all, you only ‘know’ that you are thinking of the skill’’. The major disadvantage of the VMIQ series of questionnaires, as pointed out by McAvinue & Robertson (2008), is that the tasks are described too vaguely, as an individual may image a different movement when swinging on a rope than someone else. For example one individual may be attempting to imagine a more complex movement affecting their perceived ability to imagine the action vividly. VMIQ-2 also involves a large quantity of movements (24), some of these more complex movements may be novel to the participant and so may not accurately assess movement imagery ability (McAvinue & Robertson, 2008).

Another widely used imagery questionnaire is the Motor Imagery Questionnaire (MIQ) developed by Hall & Pongrac (1983). The original MIQ was revised (MIQ-R) so as to remove the more athletic movements and shorten the number of items, from 18 to 8, making it applicable to a greater population and faster to administer (Hall & Martin, 1997). The original MIQ and MIQ-R measure both visual and kinesthetic aspects of movement imagery using instructions such as "attempt to see" or "attempt to feel" the movement. The MIQ-R reversed the rating scale of the MIQ in order to have higher numbers related to higher imagery ability. For the MIQ-R, imagery ability is rated using a 7-point Likert scale, with 1 being, " very hard to see/feel" and 7 being, "very easy to see/feel".

Recently, Williams et al., (2012) questioned the two-factor structure (visual and kinesthetic) of the MIQ-R to assess imagery ability and developed the MIQ-3 for use with healthy adults. In this revised version of the MIQ-R, the visual component of movement imagery is subdivided into external and internal visual imagery. As such, this questionnaire assesses both external and internal visual imagery, as well as kinesthetic imagery. The MIQ-3 has shown good internal reliability for each subscale with CR values of .83 (external visual), .79 (internal visual), and .85 (kinesthetic) (Williams et al., 2012). Further investigation of the validity of the MIQ-3, showed medium correlations with the values attained from the newer VMIQ-2. Specifically, in support of the concurrent validity of the MIQ-3, correlations were highest between the respective modalities (e.g. both kinesthetic) of the VMIQ-2 with correlations of 0.679 (external visual), 0.628 (internal visual), and 0.709 (kinesthetic), each of which was significant at $p < 0.001$ (Williams et al. 2008). Authors suggest that this medium correlation is due to the fact that these two questionnaires are not measuring exactly the same thing. While the MIQ measures ease of imaging, the VMIQ measures vividness of the image.

An advantage of the MIQ series of questionnaires over the VMIQ is that each of the imaged actions is preceded by the actual performance of the action. This ensures that all individuals interpret instructions similarly, as variability may occur due to different individual experience with a movement (Williams et al., 2012). The MIQ-3 has also shown predictive validity as assessed via the prediction of cognitive and motivational aspects associated with observational learning.

The MIQ-3 questionnaire is currently the only movement imagery questionnaire that has been adapted for use in children via the recently validated MIQ-C (Martini et al., 2016). Studies have utilized the adult version of the VMIQ questionnaire with children with little success (Isaac & Marks, 1994; Taktek, Zinsser, & St. John, 2008). The study by Taktek et al. (2008) utilized the VMIQ questionnaire to compare movement imagery ability to motor performance in children. The findings of the study were that there was no correlation between movement imagery ability and motor performance, which the authors attributed to the use of a questionnaire validated solely for an adult population. The children expressed difficulties with several aspects of the questionnaire including the rating scale, length of the questionnaire and procedures, as well as the concept of evaluating the vividness and clarity of what they were imagining (Taktek et al., 2008). The validity and reliability when administering a questionnaire developed for use with adults comes into question based on the complexity of the terminology and concepts associated with the measurement tool (Martini et al., 2016; Stadulis, MacCracken, Eidson, & Severance, 2002).

Although the MIQ and VMIQ series of questionnaires show similar psychometric properties (Williams et al. 2008), the aforementioned advantages, most importantly its validation in the child population, have led to the use of the MIQ-C in the current research. These measures of movement imagery have allowed researchers to quantify the covert stage of movement and potentially allow for the exploration of the relationship between the covert (movement imagery) and overt (movement action) phases of movement (Williams et al. 2008).

Relationship Between Movement Imagery and Online Control

To date, the only study to investigate the relationship between movement imagery ability and online control, did so with a healthy adult population (Hyde et al., 2013). The authors quantified movement imagery ability using a mental hand rotation task, measuring RT, and online control via a DSRT, using TTC as the principle measure. The authors used a three-step hierarchal regression analysis to investigate the effect of medial and lateral mental hand rotation individually on TTC. The first step of the regression utilized movement from non-jump trials to control for variability in general reaching efficiency between individuals. Their model accounted for 39% of the total variance in TTC, $p = 0.04$. The Hyde et al. (2013) findings suggest that movement imagery ability involves similar neural mechanisms as those responsible for online control. Neither movement imagery ability nor the ability to control movements online have been evidenced at birth, which has led researchers to further investigate these processes throughout child development (Funk et al., 2005; Johnson, 2011; Molina, Tijus, & Jouen, 2009; Van Braeckel et al., 2007).

Online Control in Children

Children are still in the process of developing the neural connections, which allow for the manual reaching control seen in adults (Johnson, 2011; Van Braeckel et al., 2007). Van Braeckel et al. (2007) utilized a DSRT in order to compare kinematic indicators associated with reaching profiles in children ages 7-10, including; time of correction (ToC), acceleration time (ACCT), and deceleration time (DECT). They observed that MT was significantly greater for 7 and 8 year olds than that of 9 and 10 year olds. This increase in MT was reflective of a greater DECT rather than ACCT, which the authors suggested is due to a greater reliance on the slower visual feedback systems in the 7 and 8-year old group. The 7-year old group also displayed an increase ToC when compared to all older groups. VanBraeckel et al.'s (2007) findings support the notion that between ages 7-10, online control strategies begin to shift away from slower visual sensory feedback towards the faster feedforward modeling process.

Current evidence suggests that in mid-childhood manual reaching control begins to shift, in a non-linear fashion, towards the proficiency seen in adulthood (Ruddock et al., 2014; Wilson & Hyde, 2013). Wilson & Hyde (2013) compared DSRT performance between four age groups (6-7; 8-9; 10-12; 20-28 years) in both chronometric and kinematic measures. They found that there was a non-linear progression with movement time (MT) and time to correction (TTC), with respect to age. The younger children (6-7 years) differed significantly in MT and TTC compared to the two groups of older children (8-9; 10-12 years). There was no significant difference in these measures between older children; however, young adults were again significantly faster than the older children. These findings were replicated in the Ruddock et al. (2014) study, and suggest that these age groups represent critical stages in the development of the rapid online control systems believed to be associated with feedforward models.

Imagery in Children

The ability to perform imagery has not been evidenced at birth. In the study by Kosslyn, Margolis, Barrett, Goldknopf, & Dally, (1990), children of ages 5, 8, and 14 were required to mentally rotate images of objects composed of blocks. They observed an inability of the 5 year old group to perform mental rotations of the images, whereas the ability was apparent in both 8 and 14 year old groups. It is important to note however, that the mental rotation was not movement imagery but rather visual imagery, which is not subject to biomechanical constraints (Takeda et al. 2010). Funk et al. (2005) investigated specifically movement imagery in children using the previously described mental hand rotation task in order to determine whether 6 year old children could utilize movement imagery. The results for RT increased with angle as expected, based on results in adults, suggesting that the 6 year olds were using movement imagery to complete the task. The pilot study, also reported in this article (Funk et al., 2005), found that the children who could not utilize movement imagery to rotate the images were all 5 year of age. Another study, investigating the development of movement imagery ability by Molina et al. (2008), analyzed the correlation between real and imagined movement time in children aged 5 and 7. The timed task involved either carrying a doll from one table to her house on another table, or imagining performing that action. While a significant correlation was found between imagined and performed MT for the 7 year olds, it did not approach significance in the 5 year old group. These studies that suggest that movement imagery ability begins to develop in children between ages 5-6 are further supported by the studies of Gabbard, Cordova, & Ammar, (2007) and Gabbard (2009).

The ability to imagine movement continues to develop until it reaches adult like levels around twelve years of age (Choudhury, Charman, Bird, & Blakemore, 2007a/b, Gabbard, 2009; Gabbard et al., 2011). Skoura, Vinter, & Papaxanthis (2009) suggest that this development is related to the development of the posterior parietal cortex (PPC) as well as several prefrontal areas of the brain. In a study of movement imagery by Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman (2009), the movement imagery ability of primary school children was assessed via a mental hand rotation paradigm. Children were divided into three groups (7-8; 9-10, 11-12 years), similar to the above-described DSRT studies. They found that the RTs for the mental hand rotation task were significantly longer for the 7-8 year old group than the two older groups. Interestingly, this significant difference in movement imagery ability occurs at a similar age to the ability to control trajectories online from the Wilson & Hyde (2013) and the Ruddock et al. (2014) studies. These findings suggest that movement imagery ability begins to develop in children between ages 5-6 and continues to develop in a non-linear pattern into adolescence. The overlap in development of the movement imagery ability, online control, and the PPC suggests that there may be a link in the neural mechanisms underlying these abilities.

Objectives and Statement of the Research Question

The similar developmental patterns of movement imagery ability and online control, along with the relationship between the two abilities described by Hyde et al. (2013), support the theory that the mental representation of action used to imagine movements is closely related to that used in the feedforward model of online control utilized in rapid reaching movements. However, it is not clear whether this relationship holds true in children. While much of the movement imagery studies with children have used implicit measures of movement imagery, the recent development of an explicit imagery measurement tool validated for children, the MIQ-C (Martini et al., 2016), allows researchers to differentiate between movement imagery perspectives so as to determine whether a particular perspective is most closely associated with the efference copy utilized in the online control of rapid reaching movements.

As such, the goal of the current study was to determine whether children's motor imagery ability is related to their ability to make mid-movement corrections in response to unexpected target perturbation in a reaching task. To attain this goal, we addressed the following research questions; 1) Does implicit movement imagery ability, as assessed by a mental hand rotation task, predict the speed of online trajectory corrections? 2) Does explicit movement imagery ability, as assessed by the MIQ-C, predict the speed of online trajectory corrections? 3) Does a particular movement imagery perspective predict the speed of online trajectory corrections? 4) Does a combination of both implicit and explicit measures predict the speed of online trajectory corrections to a greater degree than either measure alone? We hypothesized that both implicit and explicit measures of movement imagery would be significant predictors of online control on their own.

Finally, we hypothesized that a combination of both implicit and explicit measures would be a better predictor of online control than either individual measure.

Chapter II: Research Article

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Movement Imagery as a Predictor of Online Control in Typically Developing Children

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Abstract

The ability to mentally represent actions is suggested to have a role in the online control of movement in healthy adults. Children's movement imagery ability and online control have been shown to develop at similar non-linear rates. The current study investigated the relationship between movement imagery and online control in children by comparing implicit and explicit movement imagery measures with the ability to make online trajectory corrections. Imagery ability was a significant predictor of children's online control of reaching once age and general reaching efficiency were controlled for. These findings extend the proposed relationship between movement imagery and online control.

The ability of the motor system to adjust to unexpected environmental changes is essential for maintaining accuracy during goal directed actions. These adjustments require the integration of incoming sensory information regarding both target and limb positions with the current motor plan, allowing for discrepancies to be corrected (Wolpert & Ghahramani, 2000). It is proposed that the central nervous system (CNS) creates an internal representation of the sensorimotor system, termed an internal model, in order to facilitate the transformation of incoming sensory information to motor commands (Wolpert & Ghahramani, 2000). The internal model is proposed to be comprised of an inverse model, which uses current visual and kinesthetic sensory information regarding limb position and target location to create an appropriate motor plan, and a forward model which uses a predicted state estimate, including predicted incoming sensory information, as a baseline with which to compare the incoming sensory information (Wolpert & Ghahramani, 2000). Specifically, this inverse model is suggested to allow an individual to choose the correct motor plan to produce the desired displacement (Desmurget & Grafton, 2000). The nervous system then uses a series of state estimations based on the predicted sensory feedback associated with the desired motor plan to generate a detailed mental representation of the desired action, termed efference copy (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). During the movement the predicted state estimations are compared to the current sensory inflow. Should discrepancies arise, for example due to a change in target location, an error signal is generated and the motor plan is updated online to minimize the error signal (Wolpert & Ghahramani, 2000). This combination of feedfoward (predictive) and feedback processes allows for online corrections to be made rapidly in response to changes in the environment (Castiello, Paulignan, & Jeannerod, 1991; Farne` et al., 2003).

To measure one's ability to modify their ongoing movements in response to changes in the environment, researchers have typically used a reaching task in which the target sometimes changes position at movement onset (Cressman, Franks, Enns, & Chua, 2006; Desmurget et al., 1999; Goodale et al., 1986; Hyde, Wilmut, Fuelscher, & Williams, 2013; Pisella et al., 2000; Plumb et al., 2008). Participants complete most of their movements to a central target (e.g. 80% of the trials) and these movements act as a reference for determining changes in movement trajectory on perturbed trials in which the target changes position. These perturbed trials are termed jump trials as the target 'jumps' to a new position (e.g. to the left or right of the central target) at movement onset. The time at which the trajectory is corrected towards the new target location provides insight into the participant's ability to control reaching movements online. In healthy adults, changes in trajectory have been observed to occur in as little as 100 ms following a target jump when measuring the time required to make a corrective movement (Paillard, 1999).

An accurate internal model is deemed necessary to control rapid movements online and adjust trajectories in response t a target jump (Blangero, Menz, McNamara, & Binkofski, 2008; Hyde & Wilson, 2011a, 2011b; Wolpert & Ghahramani, 2000). It has been suggested that movement imagery can be used to provide insight into one's internal model or mental representations of an action associated with an internal model (Hyde et al., 2013; Jeannerod, 2001; McAvinue & Robertson, 2008). Movement imagery is the ability of an individual to mentally perform an action in the absence of overt movement

(Decety et al., 1996). Current research has shown that the same brain structures appear to be activated whether a movement is imagined or is actually produced (Jeannerod, 2001; Munzert, Lorey, & Zentgraf, 2009) and both imagined and actual movements have been shown to be subject to the same biomechanical and temporal constraints (Jeannerod, 2006). Thus, it has been suggested that imagined actions can provide insight into the mental representations of actions preceding overt movement production (Gabbard, 2009; Hyde et al., 2013; Jeannerod, 2001; Munzert et al., 2009).

To date, the ability to image movement has been determined using explicit or implicit measures, as it is recognized that movement imagery ability is multidimensional and speculated that explicit and implicit aspects may be portraying separate aspects of imagery ability (McAvinue & Roberston, 2008; 2009). Although both explicit measures and implicit measures have been validated as measures of movement imagery ability (De Lange, Helmich, & Toni, 2006; Gabbard, 2009; Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Hyde et al. 2013; Takeda, Shimoda, Sato, Ogano, & Kato, 2009; Williams, Thomas, Maruff, & Wilson, 2008; Williams et al., 2012), the natures of the respective tasks suggest that both give slightly different insight into one's ability to mentally represent actions. Explicit measures of one's movement imagery ability involve conscious mental representations of the action whereas implicit movement imagery ability is measured using unconscious mental representations of the action (McAvinue & Robertson, 2008). For example, an explicit movement imagery measure is the Movement Imagery Questionnaire (MIQ) series of subjective questionnaires (Hall & Pongrac, 1983), where individuals are explicitly asked to image themselves performing an action and then rate their ease of imaging on a 7-point Likert scale. On the other hand, the hand rotation task is an example of a task that accesses movement imagery in an implicit manner. The hand rotation task involves determining the laterality (right or left) of an image of a hand as fast as possible. The use of imagery is termed implicit, as the task does not explicitly instruct participants to use movement imagery to perform the task but instead assumes that movement imagery is required to complete the task.

Recently, the relationship between implicit movement imagery and the ability to make online trajectory corrections was investigated in healthy adults (Hyde et al., 2013). Specifically, Hyde et al. (2013) constructed a hierarchal regression model to determine if variables associated with an implicit measure of movement imagery were a significant predictor of the time to correct a movement in response to a change in target position. After controlling for general reaching efficiency, Hyde et al. (2013) found that movement imagery ability, as assessed via the hand rotation task described above, accounted for 39% of the total variance in online control. This finding supports the theory that one's ability to mentally represent actions is involved in the online control of rapid movements.

This association between online control and imagery may also exist in children as during childhood, both the online control systems involved in rapid online trajectory correction and movement imagery ability undergo rapid periods of non-linear growth. Specifically, similar patterns of non-linear change appear in both systems between 7-12 years of age (Butson, Hyde, Steenbergen, & Williams, 2014; Choudhury, Charman, Bird, & Blakemore, 2007a/b, Gabbard, 2009; Gabbard & Bobbio 2011; Ruddock et al., 2014; Wilson & Hyde, 2013). The goal of the current study was to determine whether children's movement imagery ability is related to their ability to make mid-movement corrections in response to unexpected target perturbations in a reaching task, so as to provide insight into the involvement of mentally represented actions in online control processes. More specifically, the current study attempted to answer the following three questions: i-is the implicit dimension of movement imagery ability, measured using a mental hand rotation task, a significant predictor of online control in children? ii-is the explicit dimension of movement imagery ability, as measured by the Movement Imagery Questionnaire for Children (MIQ-C), a significant predictor of online control in children?; and iii-is a combination of both implicit and explicit dimensions, a better predictor of online control than either dimension alone? Given that implicit and explicit measures of movement imagery have been suggest to access different aspects of an individuals movement imagery ability, it was hypothesized that both implicit and explicit dimensions of movement imagery would be significant predictors of online control and that together, they would account for a greater percentage of the variance in time to correction than either predictor alone.

Methods

Participants

Twenty-nine typically developing children, 15 female and 14 male, ages 7 to 12 years (*M* = 9.69, *SD* = 1.46) were recruited from summer camp programs at the University of Ottawa and word of mouth. The breakdown of age groups is illustrated in Table 1. Participants were grouped into either younger (7-9 years) or older (10-12 years) for the purpose of the analysis.

Table 1
Participant age breakdown by group

Group	Younger			Older		
Age (years)	7	8	9	10	11	12
n =	2	4	9	4	6	4

All participants were right hand dominant as determined by their scores on the Revised 4-item Edinburgh Handedness Inventory. Right-handedness was used as an inclusion criteria based on findings that handedness accounts for differences in reaction times during hand rotation tasks (Takeda et al., 2009), with faster reaction times typically observed for right-handers between the ages of 5-10 years compared to left-handers (Gabbard, Ammar, & Rodrigues, 1995). Participants were also screened to assess their risk of having Developmental Coordination Disorder (DCD), using the Developmental Coordination Disorder Questionnaire (DCDQ'07) as previous studies have shown individuals with DCD to have both decreased movement imagery ability (Williams et al., 2008) and decreased ability to correct reaching trajectories online (Plumb et al., 2008) when compared to typically developing children. No participants were determined to be at risk of having DCD and thus were not excluded from this study. Parental/guardian consent and child assent was obtained for all participants. . The study was conducted in accordance with ethical guidelines approved by the University of Ottawa Health Sciences and Science Research Ethics Board.

Measures and Apparatus

The three tasks completed by participants are described below. Task order was randomized and counterbalanced to control for order effects.

The Movement Imagery Questionnaire for Children (MIQ-C). The MIQ-C (Martini et al., 2016) was used to determine explicit movement imagery. The MIQ-C is a 12-item questionnaire where children rate their ease of imaging four simple movements; a knee raise, a vertical jump, a standing hip and lumbar flexion, and a shoulder horizontal adduction. Each movement is imagined from three different perspectives: kinesthetic (feeling the movement), internal visual (1st person) and external visual (3rd person).

The MIQ-C was administered to each participant individually, such that the primary investigator read the instructions to the participant. As per the MIQ-C instructions, participants were asked to perform a movement and then instructed to imagine the movement they had just performed from a particular perspective. The participants then rated their ease of imaging on a 7-point Likert scale.
Scores were recorded for each imagery perspective for each of the four movements totaling 12 scores. For each participant, an average score out of seven was calculated for each imagery perspective.

Hand rotation task. This task was used as an implicit measure of movement imagery ability. Stimuli consisted of 10 by 10 cm images of a single hand, presented on a 17-inch laptop computer screen. This hand rotation task was created using Qt creator v3.1.0 (The QT Company, 2014) programming software. The task required participants to correctly identify the stimuli as a right or left hand as quickly as possible. The hand stimuli consisted of a single, high resolution, palm view image of a hand. The same image was mirrored to present left handed stimuli. Palm view images were used as they have been found to illicit greater use of motor imagery than posterior view images (Ter Horst, van Lier, & Steenbergen, 2010). Hand stimuli were presented randomly with rotations of 45° increments (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, 360°). A stimulus with vertical fingers was considered to be at 0°. The stimulus remained on the screen until a keypress response was provided.

Participants sat in an adjustable desk chair facing the laptop screen with the left and right index or middle fingers (as per preference) resting on the (A) and (‘) keys respectively. Distance from the screen was based on a comfortable arm position for the participant in which, he/she was able to rest their forearms on the table with a straight back and have their index or middle fingers resting on the designated keys. The (A) key was labeled with a red circle, for left handed image responses, and the (‘) key with a green circle, for right handed image responses, in order to allow participants to easily distinguish the correct keys. Participants were given a verbal description of the task followed by a visual demonstration of five trials by the primary investigator in which he verbally identified the stimuli as right or left to the participants in order to ensure their understanding. Participants then performed five practice trials with feedback. Feedback included whether responses were correct/incorrect, as well as a reminder that all hands were palm views. If the participant failed to respond correctly to a minimum of two of the five stimuli, they were allotted five subsequent practice trials, again with feedback. This occurred in one case, however, the participant reported they had misunderstood the palm view only images and had answered based on dorsal views. This participant’s second set of practice trials supported this admission and the participant was included in the analysis. Participants gave verbal confirmation of their understanding of the task upon completion of the practice trials. Following the practice trials, participants completed a test block of 48 trials. Recorded measures included reaction time (RT), the time from stimulus display until key press, recorded to the nearest 1ms, and accuracy (ACC).

Double-step reaching task (DSRT). The DSRT was used to assess online control. The custom software for the task was also programmed using QT creator (The

QT Company, 2014). Stimuli were displayed on the above described 338 x 270 mm laptop in order to allow a 1:1 ratio between displayed movement distance and actual movement distance of the reach, which was performed on a Wacom Intuos Pro 5 graphics tablet (325 x 203 mm active area). The tablet was placed flat on the desk directly in front of the laptop and required participants to reach as quickly and accurately as possible with a stylus from the home base (1cm diameter) to one of three targets (1cm diameter) located 16 cm above the home position, at 0° or 20° to the left or right of the center target. A trial began once the participant had oriented the cursor, by using the stylus on the tablet, into the home position for 2 seconds. Following the delay, the central target appeared, serving as a go signal. For 80% of the trials the target location remained stationary at the central position (non-jump trials). For the remaining 20% of the trials, the target was shifted to the left or right target location at movement onset, which was defined as the point in time when the cursor left the home position (jump trials). The trial order (jump/non-jump) was randomized for each participant.

Participants sat facing the laptop while holding the stylus in their right hand with their fingers gripping the stylus as close to the tip as possible in order to control for participants moving their limb and changing only the angle of the stylus rather than position. The distance from the screen and seat position was similar to that of the hand rotation task, with participants sitting with a straight back and forearms able to rest flat on the desk. In this case, the graphics tablet was placed directly in contact with the front edge of the laptop and participants were able to rest the stylus on the home position comfortably. The seat was adjusted to allow participants to be in a comfortable writing position, which the participant verbally confirmed was how he/she would write in everyday life. Participants were given a verbal description of the task followed by a visual demonstration of a jump and non-jump trial by the primary investigator. Following the demonstration, participants were reminded to perform each trial as quickly and accurately as possible, as well as to maintain contact between the stylus and the tablet at all times. Participants then performed 10 practice trials (also comprised of 80% non-jump, 20% jump trials) followed by two blocks of 50 test trials. Recorded measures included movement time (MT) and time to correction (TTC).

Procedures

Participants were all tested using the same apparatus, however, the test location differed for several participants. In order to accommodate participants who could not attend the University of Ottawa testing sessions, the primary investigator tested several participants at their homes. All testing was performed one on one in a quiet location in order to minimize distractions. The seating and distance criteria where maintained regardless of testing location.

Analyses

MIQ-C (explicit movement imagery). Results for the MIQ-C were recorded for the three separate subscales: kinesthetic imagery (KI), internal visual imagery (IVI), external visual imagery (EVI). A one-way analysis of variance (ANOVA) was conducted to determine whether imagery score differed based on perspective (IVI, EVI, and KI). A one-way ANOVA was also performed to determine the effect of age on the overall reported imagery score. The overall imagery score was the sum of the three imagery scales (Gabbard & Lee, 2014).

Hand rotation task (implicit movement imagery). Mean response time (RT) was calculated for images of both left and right hands at each angle. Both correct and incorrect responses were included in the mean response time calculations, although outliers were removed. Outliers were deemed to be response times ±2.5 standard deviations away from the mean at each angle for each participant. For the remaining trials, response times were then categorized into either a medial (left hand: 45°, 90°, 135°; right hand: 225°, 270°, 315°) or a lateral response (left hand: 225°, 270°, 315°; right hand: 45°, 90°, 135°). Paired sample t-tests were performed between lateral and medial stimuli response times in order to confirm that the task was subject to biomechanical constraints (i.e. response time was greater in response to lateral stimuli compared to medial stimuli, as this movement is more unnatural). A similar paired sample t-tests was performed for lateral and medial response accuracy (ACC), for which no difference was expected (Hyde et al., 2013). To further support that the task adhered to biomechanical constraints, as well as investigate the effect of age, two seperate two-way ANOVAs were performed to determine the effect of age and angle on both response time and response accuracy. This also allowed the detection of any potential interaction between angle and age.

Double step reaching task (online control). Trials were separated based on target location into either non-jump, jump left, or jump right trials. Each trial was analyzed individually in order to visually determine if an error had occurred. Errors included reaches that paused for a period of time as reflected by the velocity and acceleration graphs which is characterized by a 0m/s and $0m/s^2$ repeat for greater than 50ms, and thus were not smooth and continuous reaches, as well as reaches on which participants failed to follow protocol; for example drawing a circle around a target. Five error trials were excluded from the MT and TTC calculations. Also excluded were outliers in either of our measured variables. Outliers were defined as responses ±2.5 standard deviations from the mean, however, after eliminating error trials only two trials were discarded. MT was defined as the time between the stylus leaving home base (passing through +20 pixels (0.4cm) in the y-direction) and the time the stylus contacted the target. In order to determine TTC, a mean path trajectory based on non-jump trials was calculated for each participant along with the two standard deviation range. This path was calculated by averaging the x-position at each interval increase in y-position. Each individual jump trial was then compared to the mean path to determine at what point the current perturbed trial path intercepted the two standard deviation limit indicating that a corrected movement had been initiated. From this point we worked backwards to visually identify the point where the trajectory was modified to move in this new direction using position and velocity profiles of the jump trial. The point determined to be the TTC was the point at which the acceleration, velocity, and position profiles shifted to a consistent positive (+20° jump trial) or negative (-20° jump trial) in the x-direction based on the jump trial location. Similar visual determinations of TTC have been used in previous studies (Hyde et al., 2013, Pissela et al., 2000; Ruddock et al., 2014; Van Braeckel et al., 2007).The total TTC was calculated based on the average of both left and right jump trials TTC. A paired-samples t-test was used to compare mean MT for jump and non-jump trials (Hyde et al., 2013; Ruddock et al., 2014). A one-way repeated measures ANOVA was performed to investigate the effect of age on TTC (Ruddock et al., 2014). This effect was predicted based on the developmental period of online control of our sample population.

Relationship between online control and movement imagery. The current study aimed to determine whether an implicit dimension, explicit dimension, or a combination of both implicit and explicit dimensions of movement imagery ability was the best predictor of online control in children. To determine this, three different hierarchal models were constructed using variables from the hand rotation task, MIQ-C, and DSRT. The dependent variable utilized in each model was TTC as determined from the DSRT jump trials. This variable is widely used as a measure of an individual's ability to make online corrections in a DSRT (Hyde et al., 2013; Ruddock et al., 2014). Key variables in the models included lateral and medial RT and ACC from the hand rotation task, as well as imagery scores of each of the three imagery subscales (EVI, IVI, KI) obtained via the MIQ-C. For the explicit measure, each of the imagery subscales was entered in the model so as to determine whether one of the perspectives was a more significant predictor of TTC than the other two. Three different models were tested in order to address each of our three research questions.

Model 1 was analyzed in order to determine whether the implicit dimension of movement imagery ability, as assessed via the hand rotation task, was a significant predictor of TTC in children. In previous work it has been shown that in school age children both online control and imagery ability increase across age in a non-linear fashion (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Hyde et al., 2013; Molina, Tijus, & Jouen, 2008; Wilson & Hyde, 2013; Ruddock et al., 2014). More specifically, Ruddock et al. (2014) found an effect of age on the time to correction in children. As such, in the current study it was necessary to control for age in the first step of our hierarchal regression analysis. In Hyde et al. (2013)'s study with adults, the second step of the model was to control for the general reaching efficiency (mean movement time on non-jump trials) as this has a significant effect on TTC. Finally, similar to Hyde et al. (2013), both lateral RT/ACC and medial RT/ACC for the hand rotation task were added to the model in the final step of the regression model.

The second model was constructed in order to determine whether explicit movement imagery ability, assessed by the MIQ-C, was a significant predictor of TTC in children. Similar to Model 1, the first two steps of the model controlled for age and general reaching efficiency respectively. For the third step of the model, each of the three imagery perspective (EVI, IVI, KI) were inserted to determine if any or all of the perspectives accounted for a significant amount of the variance in TTC.

Model 3 was tested to determine if a combination of both implicit and explicit dimensions was a better predictor of TTC than one measure alone. This model utilized a combination of the best predictors of TTC from both objective measures from Model 1 (Medial MT & ACC) and subjective measures from Model 2 (KI).

Results

Movement Imagery

The results of the three tasks will be discussed below, followed by the results of the three hierarchal regression models used to predict TTC.

MIQ-C. ANOVA revealed no significant imagery score based on perspective, $F(2, 87) = 2.179$, $p = .111$ (see Figure 1). The effect of age on overall imagery score failed to reach significance, $F(1,28) = 2.342$, $p = .138$.

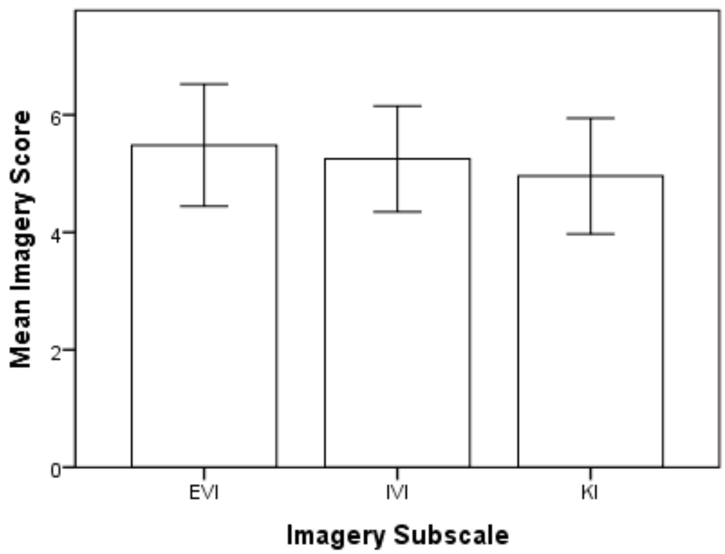

Figure 1. MIQ-C mean imagery score by imagery subscale. Error bars represent ± 1 standard deviation.

Hand rotation task. Figures 2 show the effect of angle of rotation on mean reaction time and accuracy respectively in the hand rotation task. Trends in both mean reaction time and accuracy follow previous research (Funk et al., 2005; Hyde et al., 2013), in that mean reaction time increased and accuracy decreased with increasing angle of rotation of the image from the vertical (0°). However, neither mean reaction time ($F(4, 145) = .620$, $p = .649$) nor mean accuracy ($F(4, 145) = .242$, $p = .914$) differed significantly across angles of rotation. The lack of significant effects is likely related to the diverse range of imagery ability levels in the current sample, as the sample is representative of a period of rapid development (ages 7-12) with regards to imagery ability. This large range of imagery ability may have increased the variance in reaction time compared to previous studies with healthy adults (Hyde et al., 2013), as evidenced in Figures 2, thus, making it unlikely that any effect be found significant. Figure 3 illustrates the effect of age on mean reaction time.

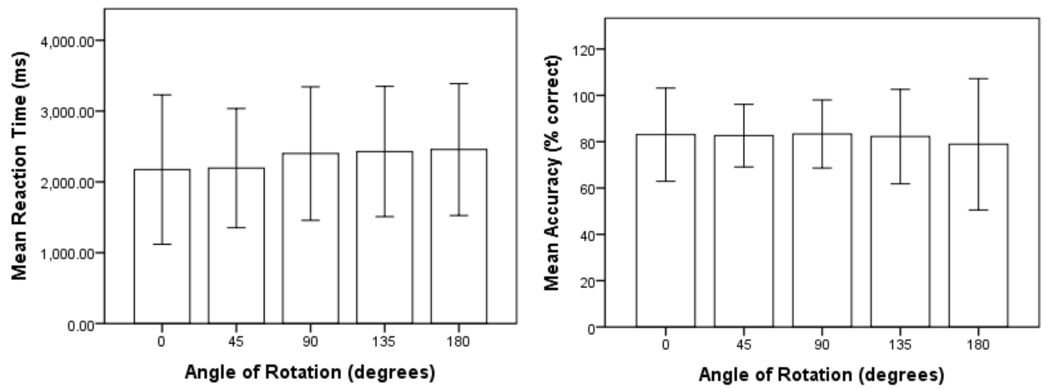

Figure 2. Hand rotation task mean reaction time and mean accuracy by angle of rotation calculated from both medial and laterally rotated stimuli. Error bars represent ± 1 standard deviation.

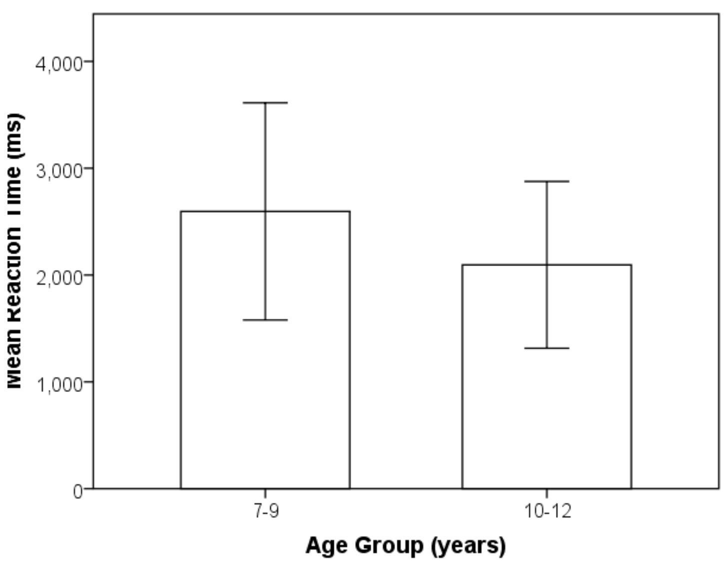

Figure 3. Hand rotation task mean reaction time by age group. Error bars represent ± 1 standard deviation.

A two-way ANOVA was conducted to determine the effects of age and angle of rotation on mean reaction time and accuracy. Age displayed a significant effect on both mean reaction time, $F(1,135) = 10.551$, $p = .001$, and accuracy, $F(1,135) = 5.495$, $p = .021$. Age was determined to have an inverse effect on reaction time, such that older children displayed decreased reaction time. Accuracy, on the other hand, was evidenced to increase in older children. Angle of rotation did not display an effect on mean reaction time, F (4,135) = .644, p = .632, or accuracy, F (4,135) = .237. p = .917. There was no interaction evidenced between age and angle in either mean reaction time, F (4,135) = .100, p = .982, or accuracy, F (4, 135) = .067, p = .992. The effect of age on performance in a hand rotation task supports previous data (Butson et al., 2014; Caeyenberghs et al., 2009; Wilson & Hyde, 2013; Ruddock et al., 2014), suggesting that movement imagery ability improves or other perceptual motor skills improve with age.

Table 2
Descriptive Statistics for the Double-Step Reaching Task.

	Movement Time (Non-Jump)	Movement Time (Jump)	Time to Correction
Mean	775	1062	332
SD	151	177	30

Differences in mean reaction time and mean accuracy between laterally and medially rotated stimuli were analyzed to confirm that the hand rotation task was subject to biomechanical constraints. Mean reaction time was significantly longer for laterally rotated stimuli than in those that were medially rotated, t (29) = 4.990, p < .001, Cohen's d = -.50. There was no significant difference in accuracy between stimuli with medial versus lateral rotations, t (29) = -1.821, p = .076, Cohen's d = .42. The increased reaction time associated with laterally rotated stimuli when compared to those rotated medially is congruent with the literature (Hyde et al., 2013) suggesting that implicit movement imagery was used in the task, thus validating the effectiveness of the task as an implicit movement imagery measure.

Double step reaching task Descriptive statistics for the online control task variables are depicted in Table 2. As expected, MT was significantly longer on jump trials when compared to non-jump trials, $t(29) = 17.972$, $p < .01$. Age was found to have a significant inverse effect on TTC, $F(1, 27) = 10.822$ $p = .003$, meaning that as children age the time required to make online trajectory corrections decreases.

Relationship Between Online Control and Movement Imagery

Model 1. Age was found to account for 26.0 % of the variability in TTC, $F(1, 27) = 10.82$, $p = .003$. Mean non-jump movement time accounted for an additional 17.0% of the total variance in TTC. Given the results of Hyde et al. (2013), both lateral RT/ACC and medial RT/ACC from the hand rotation task were added to the model in step 2 and these were found to account for a significant amount of the total variance in TTC. When both lateral and medial mean RT/ACC were added R-square change failed to reach significance $F(4, 22) = 2.316$, $p = .089$, thus, the model was not able to account for a greater proportion of the variance in TTC. When lateral and medial measures were added into the model individually only medial RT improved the model significantly, $F(2, 24) = 4.28$, $p = .026$. The final version of Model 1, along with included predictors is depicted in Table 3.

Table 3

Three-Step Hierarchical Regression Outcomes With Age, Mean Non-Jump Movement Time, Medial Hand Rotation Response Time and Accuracy as Predictors.

Model	R^2	ANOVA ΔF	Sig. ΔF	df	B	Regression SE B	Coefficients β	p
Step 1	.260	10.82	.003	1,27				
Age					-32.26	9.81	-.535	.003
Step 2	.430	9.09	.006	1,26				
Age					-10.80	11.17	-.179	.342
NJMT					.116	.038	.558	.006
Step 3	.545	4.28	.026	2,24				
Age					-11.46	9.99	-.190	.263
NJMT					.078	.037	.376	.044
MRT					.016	.006	.410	.009
					35.71	24.77	.191	.162
MACC								

Note: NJMT = Non-Jump Movement Time, MRT = Medial Hand Rotation Response Time, MACC = Medial Hand Rotation Accuracy

Model 2. The first two steps of Model 2 were identical to Model 1 in order to control for age and general reaching efficiency. The addition of all three imagery perspectives in the third step did not elicit a significant change in the R statistic, p = .451. When each of the imagery perspectives were inserted individually in step three the following R-change statistics were observed; IVI: R = .002, p = .750; EVI: R = .046, p = .134; KI: R = .021, p = .318. When entered either together or individually, no combination of imagery perspectives were found to significantly affect the model.

Model 3. Based on Model 2 the EVI (3rd person) perspective was the closest perspective to significantly changing the model and was therefore included as the subjective measure. Medial MT/ACC was used as the objective measure as it was the most significant predictor of the objective measures based on Model 1. The third step of Model 3 involved the combined addition of medial MT/ACC and EVI score in a single step. The model summary is illustrated in Table 4. This model improved the variance accounted for in Model 1 from 54.5% to 55.9% in Model 3, suggesting that while the hand rotation task alone is a more significant predictor of TTC in children than the MIQ-C alone, a combination of both hand rotation task and MIQ-C accounts for a greater amount of the total variance of TTC.

Table 4

Three-Step Hierarchical Regression Outcomes With Age, Mean Non-Jump Movement Time, Medial Hand Rotation Response Time and Accuracy, and External Visual Imagery Score as Predictors.

Model	R^2	ANOVA ΔF	Sig. ΔF	df	B	Regression SE B	Coefficients β	p
Step 1	.260	10.82	.003	1,27				
Age					-32.26	9.81	-.535	.003
Step 2	.430	9.09	.006	1,26				
Age					-10.80	11.17	-.179	.342
NJMT					116	.038	.558	.006
Step 3	.559	3.52	.031	3,23				
Age					-9.54	9.945	-.158	.348
NJMT					.075	.036	.362	.050
EVI					-5.31	4.03	-.176	.200
MRT					.015	.006	.380	.015
					-36.07	24.40	193	.153
MACC								

Note: NJMT = Non-Jump Movement Time, MRT = Medial Hand Rotation Response Time, MACC = Medial Hand Rotation Accuracy, EVI = External Visual Imagery Score

Discussion

The feedforward modeling theory of online control of rapid movements suggests that online trajectory corrections arise due to an internal model of the movement (Desmurget & Grafton, 2000; Wolpert & Ghahramani, 2000). Recent empirical work supports the overlap of motor representations associated with online control in reaching and those involved in movement imagery by illustrating that movement imagery ability is a significant predictor of the time required to modify one's trajectory in response to a change in target position during rapid reaching movements in an adult population (Hyde et al., 2013). However, while this relationship has been demonstrated in adults, no study to date has investigated this relationship during the developmental years of childhood. The purpose of the current study was to determine the relationship between movement imagery and the ability to make online trajectory corrections in rapid reaching tasks in children. Similar to adults, once age and general reaching efficiency effects were controlled for, movement imagery ability in children was found to be a significant predictor of the ability to correct trajectories online. While the implicit dimension of movement imagery ability alone was a significant predictor, the model accounting for the most variance was generated using a combination of both implicit and explicit imagery measures.

Due to biomechanical and temporal constraints associated with movement imagery, more biomechanically challenging movements or movements that require more time to perform have been shown to take longer to image than more easily performed actions (Jeannerod, 2006; McAvinue & Robertson, 2008; Munzert et al., 2009; Munzert & Zentgraf, 2009). In the case of hand rotation tasks, our implicit measure of movement imagery ability, medial rotations of the hand stimuli should elicit shorter response times than those to lateral stimuli. Also, increasing the angle of rotation should lead to an increase in the reaction time. It was therefore important to investigate these effects in the current study to ensure the proper design of the custom hand rotation task. We found that medial stimuli elicited a significantly faster response than lateral stimuli. Interestingly, contrary to our findings, Hyde (2013) observed lateral measures to be more valuable in the model. We suggest that, in children, movement imagery ability may not have attained the required level to distinguish laterality of the more biomechanically awkward, laterally rotated, stimuli at the same consistency and speed as a healthy adult population. The shorter RT associated with medially rotated stimuli is in line with previous findings (Funk, Brugger, & Wilkening, 2005; Hyde et al., 2013; Ter Horst et al., 2010) suggesting that the current task was subject to biomechanical constraints of the task. However, we found that accuracy was not significantly different between medial and lateral stimuli. This lack in discrepancy between stimuli accuracy based on angle of rotation can be attributed to a ceiling effect as accuracy approached 90%. Contrary to typical studies involving hand rotation tasks (Funk, Brugger, & Wilkening, 2005; Hyde et al., 2013; Ter Horst et al., 2010), the effect of angle of rotation on reaction time in the present study failed to reach significance. However, the small sample size in each age group included in our study may have been a limiting factor with regards to the lack of significance. While our current findings support the use of this task to measure movement imagery ability, the knowledge that the designed hand rotation task was based on the task described by Hyde et al. (2013) increases the likelihood that the current task was a valid measure of implicit movement imagery. These findings also support that children are capable of utilizing movement imagery to perform the hand rotation task.

The MIQ-C was used as our explicit measure of movement imagery ability. This measurement tool was recently developed in order to better assess each of the three imagery subscales in children, external visual, internal visual, and kinesthetic. Due to the novelty of the MIQ-C, there is limited literature with which to compare findings. However, the observed pattern of ease of imaging scores in the current study mimics the pattern found in the only current published study of the MIQ-C (Martini et al., 2016) with EVI scoring the highest, followed by IVI, and finally KI. While the body of literature is scarce due to the novelty of the MIQ-C as a movement imagery ability measurement tool, our findings suggest that the external visual imagery perspective is the most developed perspective in childhood. We suggest that the higher ability when imaging from the EVI perspective relates to the 3rd person perspective used throughout childhood to learn movement patterns via observational learning (Wang, Meltzoff, & Williamson, 2015; Williamson, Jaswal, & Meltzoff, 2010).

While reaction time was not recorded, the custom software controlled for the potential of a target perturbation occurring prior to take off by delaying the perturbation until the stylus had left the home base area. As predicted, movement time was significantly longer in jump-trials than compared to non-jump trials. Compared to previous studies involving similar populations (Ruddock et al., 2014: Wilson & Hyde, 2013), the TTC in the current study fell between the typically observed 300-400ms time observed, even though the distance of the reach was not consistent between studies. The current data appear to be consistent with the previous studies (Ruddock et al., 2014: Wilson & Hyde, 2013) conducted in similar populations suggesting that children follow a typical developmental pattern within the ages of 7-12 years.

Three models were tested in the current study. Model 1 was used to investigate variables associated with implicit imagery ability (objective measure) as predictors of TTC. The first two steps of Model 1 were used to control for both age and general reaching efficiency which are known to influence TTC in children (Hyde et al., 2011; Hyde et al., 2013; Ruddock et al., 2014: Wilson & Hyde, 2013). Age and general reaching efficiency accounted for 26.0% and 17.0% of the variance in TTC respectively for a total of 43.0% of the total variance. The third step of the regression required the inclusion of performance on both medial and lateral hand rotations in the hand rotation task. When both medial and lateral hand rotation performance variables were added together in step 3 of Model 1, the R-square change failed to reach significance. When entered individually in step 3 only medial rotation performance variables (RT and ACC) were found to significantly improve the model accounting for an additional 11.5% of the variance in TTC.

In the study by Hyde et al. (2013), the model that included lateral reaction time and accuracy in the hand rotation task was found to be a better predictor of TTC than medial reaction time and accuracy healthy adults. However, when compared to medial reaction time and accuracy, the current analysis found the inverse to be true in children. Reaction time and accuracy in laterally rotated stimuli failed to achieve significance when included as predictors in the current model whereas reaction time and accuracy in medially rotated stimuli were found to be significant predictors. Hyde et al. (2013) attributed the lack of significance in reaction time and accuracy of medially rotated stimuli in the model to ceiling effects due to the basic nature of the task. The children in the current study obtained longer mean reaction times for the hand rotation task than those of adults in previous studies (Hyde et al., 2013; Hyde et al., 2014; Takeda et al., 2009) and so we suggest that the imagery ability of the children may not have attained an adult like level, leading to greater variability in their responses to the laterally rotated stimuli. This is further supported by the previous imagery study comparing children and youth movement imagery ability to that of an adult where they demonstrated that movement imagery ability does not attain adult-like levels until age 12 (Wilson & Hyde, 2013).

Due to the greater biomechanical constraints of the action required for the lateral rotations in the hand rotation task, these have been suggested to require a more developed movement imagery skill (Hyde et al., 2013; Jeannerod, 2006; McAvinue & Robertson, 2008; Munzert et al., 2009). However, based on the current findings, we suggest that children's movement imagery ability has yet to attain the level required for ceiling effects observed in medial response time in adults (Hyde et al., 2013), thus, making it a significant predictor of TTC in children. Furthermore, because movement imagery ability may not develop at the same age in all children, a lack of development of movement imagery ability in older children may lead to a greater variability of lateral performance within a specific age and an overlap in lateral rotation performance between groups. These differences in movement imagery ability between children and adults, as well as the developmental maturity of children of the same age, may account for the inclusion of the less biomechanically challenging medial stimuli reaction times.

The current findings indicate that movement imagery ability, as measured by the hand rotation task, accounts for a significant amount of the variance in TTC in children. These findings extend the work of Hyde et al. (2013), and together suggest that these abilities are related through a significant portion of the human lifespan.

Model 2 investigated whether explicit movement imagery ability was a significant predictor of TTC in the children. There was no combination of imagery subscales that was able to account for a significant amount of the variance in the current model. While Model 2 failed to demonstrate a significant predictor of TTC, it identified the EVI perspective as most likely improve the model when included along with the implicit imagery ability predictors (medial RT & ACC) determined in Model 1. This led to us to explore Model 3 where we found that the addition of both implicit and explicit measures was a better predictor of TTC.

Due to the novelty of the MIQ-C and investigations pertaining to imagery perspectives in children, there is currently a gap in the research with regards to why EVI scores are higher than other perspectives in children and why they would be more closely associated with online control. We suggest that children spend a significant amount of time learning through observation (Barr, Dowden, & Hayne, 1996; Meltzoff & Gopnik, 1993; Meltzoff & Moore, 1994). Observation is associated with a 3rd person perspective, as is EVI (White & Hardy, 1995).

Studies have shown that children as young as 6 weeks are able to observe and recreate movements observed in others (Meltzoff & Moore, 1994). For example, as early as 6 weeks of age, infants are able to imitate a movement performed by an adult, not only immediately following the observed movement, but also 24 hours post observation (Meltzoff & Moore, 1994). Since the movement was reproducible 24 hours post observation they hypothesized that there must be some representation in long-term memory that is accessible. It is important to note that an assumption being made here is that the mental representation is in the same perspective as the movement was observed (3rd person perspective). Barr et al. (1996) also investigated the ability of infants to reproduce observed actions 24 hours post observation. They determined that 12 month olds are able to reproduce significantly more movements 24 hours post observation than 6 month olds suggesting that the infants' ability to represent actions in long-term memory are developing at a very young age. Williamson, Jaswal, & Meltzoff (2010) observed that children who were able to view the act of sorting object based on colour or sound were better able to sort the objects properly than those who were only witness to the end state and instructions. By 4 years of age, children are able to sort objects based on weight by observing an adult perform that task, as well as generalize this weight sorting method to novel objects (Wang, Meltzoff, & Williamson, 2015). These studies are examples that suggest that because children may be accustomed to learning through observation and developing skills via this 3rd person perspective, we suggest this may account for more rapid development of EVI ability. This ability to learn through observation of movements has been linked to imagery ability in adult athletes of varying levels of experience in sport (Williams & Cumming, 2012). The relationship between observational learning and movement imagery is further supported by Lawrence, Callow, & Roberts (2013), who investigated the relationship between movement imagery and observational learning of a novel gymnastic skill in adults. Their study utilized the Vividness of Movement Imagery Questionnaire-2 (VMIQ-2) to assign participants into either high-level or low-level imagers. This was followed by five actual attempts at the novel skill, which were given performance scores. Both groups then received a 14 day observational learning intervention followed by a retest of the same gymnastics skill. While both low-level and high-level imagers improved on performance, the degree of improvement was significantly greater in high-level imagers. The authors suggested that observational learning ability is moderated by movement imagery ability.

The model accounting for the largest proportion of variance in TTC (55.9%) was Model 3, which combined the best predictors from both implicit and explicit movement imagery ability measures based on Model 1 and Model 2. The best predictors from the hand rotation task (implicit) were the medial rotation performance measures (RT & ACC) and the only predictor approaching significance from the MIQ-C (explicit) was EVI score. Since both the hand rotation task and MIQ-C assess slightly different aspects of movement imagery ability it was hypothesized that a combination of both implicit and explicit measures would give us a more complete estimate of movement imagery ability and thus, account for a greater amount of the total variance in TTC. The finding that a combination of both implicit and explicit movement imagery measures is a better predictor of online control than either measure individually suggests that neither measure alone paints a complete picture of an individual's movement imagery ability. This concept is supported by the previous work of Lequerica, et al. (2002), who compared multiple subjective and objective movement imagery measures, which included a hand rotation task in the objective category and a previous version of the MIQ (MIQ-R) in the subjective category. These researchers found objectively measured movement imagery ability and subjectively measured movement imagery ability to be unrelated. It is also important to note that by using a more complete measurement of movement imagery ability the relationship between movement imagery and online control was more pronounced, further supporting previous findings that the processes are related (Hyde et al., 2013). We suggest that future research utilize a combination of implicit and explicit movement imagery assessment tools in order to more accurately depict movement imagery ability.

Limitations

While the model accounting for the greatest variance in TTC included both implicit and explicit measures of movement imagery ability, increased the percent of variance explained by 1.4%. While, some may question whether this is worth the increase in model complexity, we believe that it is important to recognize EVI as part of the predictors included in the model, given the recognition that movement imagery ability is multidimensional (McAvinue & Roberston, 2009) and that this variable was determined a priori reflecting that subject matter knowledge guided the model building (Harrell, 2001).

Although the current findings suggest that movement imagery ability accounts for a significant amount of the variance in TTC, a significant amount of the variance is left unexplained. The current model however, fails to incorporate the effect of experience on the rate of development of both movement imagery ability and the ability to make online corrections during goal directed reaching. While movement imagery and online control are inherent skills in humans, they are also influenced by environmental factors. It is well documented that experience performing a skill improves an individual's ability to complete that skill. This concept has been investigated in terms of mental represented actions as well as adapting moving trajectories during rapid movements in sport. Previous studies of reaction time in professional athletes have shown that athletes do not have faster reaction times when compared to a normal sample, both of which have a reaction time of approximately 200ms (Land & McLeod, 2000; Starkes & Deakin, 1984). The similar reaction times suggest that the differences in performance between professional athletes and the general population occur during the course of the action. In baseball a 100mph pitch takes approximately 400ms to reach the plate and is only in the range of the bat for around 5ms, reaction time alone is too slow to adapt and forward models must be used in order to adapt trajectories to the pitch (Epstein, 2013; McLoed, 1987). Professional cricket players have also displayed improved ability to predict the path of the ball when watching a video of a bowl that is occluded at the halfway point when compared to amateur players. This suggests that their mental representation of the cricket bowler and ball movement patterns is likely more refined than those of novice players (Abernethy et al., 2008). However, these detailed mental representations skills are not completely transferable. When several of the most prolific hitters in professional baseball were asked to hit a professional softball pitch, which is thrown underhand rather than overhand and uses a much larger ball, they were unable to make contact in three straight at bats (Epstein, 2013). This suggests that experience with a specific observed movement pattern allows for it to be refined and used more efficiently to adapt movements to complete a goal directed movement. This skill however, is not necessarily generalizable to very different movement patterns. Experience affects the ability to generate an accurate mental representation that can be used to adapt trajectories and therefore, a child's involvement in sport is likely to have an effect on both movement imagery ability and ability to make online trajectory corrections. However, a previous study of movement imagery performance in children who participate in sport, music, or neither has shown no relationship between participation in sport or music and movement imagery performance during a hand rotation task (Dey et al., 2012). While this study appears to refute the importance of experience being incorporated into a similar model to that of the current research, it is important to reiterate that an implicit movement imagery measure, such as a hand rotation task does not paint a complete picture of movement imagery ability. It is also important to note that the movement imagery perspective most closely associated with a particular sport will not necessarily be the most closely associated with another. We suggest that the aforementioned study has defined participation in sport and music to vaguely to discount the effect of experience on movement imagery, and potentially online control. Experience therefore, is a necessary variable to be inserted into the model in future research as we suggest it may account for a significant amount of the remaining variance.

Conclusion

The ability to effectively correct trajectories on line has recently been empirically linked to the ability to mentally represent actions in a healthy adult population. In children, however, both skills are under periods of rapid development. It was hypothesized that should these processes be related, such that movement imagery should remain a predictor of online control measures during developmental years. The current study found the relationship to hold true during the ages in which both movement imagery ability and online control development takes place, further suggesting that movement imagery and online control linked throughout life.

The current study further extends previous research of imagery ability, which has focused on which movement imagery perspective is most associated with a particular task or skill (Hardy & Callow, 1999; White & Hardy, 1995; Williams, et al., 2012). Also, prior to the current study, there was no empirical evidence, in any population, to support which of the three theoretical imagery perspectives was more closely associated with the feedforward processes used in online control. The EVI perspective was determined to be the most accurate perspective in terms of predicting online control efficiency based on the current model, which combined both implicit, and explicit imagery measures. Future studies should focus on investigating the relationship between movement imagery ability and perspective, and online control in populations suffering deficits in these two abilities such as individuals with DCD, who were excluded from the current study. If the relationship were to remain consistent further support the relationship between online control and movement imagery, as well as suggest more information on the origin of the deficit.

References

Barr, R., Dowden, A., & Hayne, H. (1996). Developmental changes in deferred imitation by 6- to 24-month-old infants. *Infant Behaviour and Development, 19*, 158-170.

Blangero, A., Menz, M. M., McNamara, A., & Binkofski, F. (2009). Parietal modules for reaching. *Neuropsychologia, 47*(6), 1500-1507.

Butson, M. L., Hyde, C., Steenbergen, B., & Williams, J. (2014). Assessing motor imagery using the hand rotation task: Does performance change across childhood? *Human Movement Science, 35*, 50-65.

Caeyenberghs, K., Wilson, P. H., van Roon, D., Swinnen, S. P., & Smits-Engelsman, B. C. (2009). Increasing convergence between imagined and executed movement across development: Evidence for the emergence of movement representations. *Developmental Science, 12*(3), 474-483.

Castiello, U., Paulignan, Y., & Jeannerod, M. (1991). Temporal dissociation of motor responses and subjective awareness. A study in normal subjects. *Brain : A Journal of Neurology, 114 (Pt 6)*(Pt 6), 2639-2655.

Choudhury, S., Charman, T., Bird, V. & Blakemore, S. J. (2007a). Adolescent development of motor imagery in a visually guided pointing task. *Consciousness and Cognition, 16*(4), 886-896.

Choudhury, S., Charman, T., Bird, V. & Blakemore, S. J. (2007b). Development of action representation during adolescence. *Neuropsychologia, 45*(2), 255-262.

Cressman, E. K., Franks, I. M., Enns, J. T., & Chua, R. (2006). No automatic pilot for visually guided aiming based on colour. *Experimental Brain Research, 171*(2), 174-183.

Cressman, E.K., Cameron, B.D., Lam, M.Y., Franks, I.M., & Chua, R. (2010). Movement duration does not affect automatic online control. *Human Movement Science. 29*, 871-881.

de Lange, F. P., Helmich, R. C., & Toni, I. (2006). Posture influences motor imagery: An fMRI study. *Neuroimage, 33*(2), 609-617.

Decety, J. (1996). Do imagined and executed actions share the same neural substrate? *Brain Research.Cognitive Brain Research, 3*(2), 87-93.

Deconinck, F. J., Spitaels, L., Fias, W., & Lenoir, M. (2009). Is developmental coordination disorder a motor imagery deficit? *Journal of Clinical and Experimental Neuropsychology, 31*(6), 720-730.

Desmurget, M., Epstein, C. M., Turner, R. S., Prablanc, C., Alexander, G. E., & Grafton, S. T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2*(6), 563-567.

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423-431.

Dey, A., Barnsley, N., Mohan, R., McCormick, M., McAuley, J. H., & Moseley, G. L. (2012). Are children who play a sport or a musical instrument better at motor imagery than children who do not?. *British Journal Of Sports Medicine*, *46*(13), 923-926.

Epstein, D. (2013). *The sports gene: inside the science of extraordinary athletic performance*. New York, New York, U.S.A.: Penguin Group.

Farne, A., Roy, A. C., Paulignan, Y., Rode, G., Rossetti, Y., Boisson, D., & Jeannerod, M. (2003). Visuo-motor control of the ipsilateral hand: Evidence from right brain-damaged patients. *Neuropsychologia, 41*(6), 739-757.

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*, 402–408.

Gabbard, C. (2009). Studying action representation in children via motor imagery. *Brain and Cognition, 71*(3), 234-239.

Gabbard, C., & Bobbio, T. (2011). The inability to mentally represent action may be associated with performance deficits in children with developmental coordination disorder. *The International Journal of Neuroscience, 121*(3), 113-120.

Gabbard, C., & Lee, J. (2014). A comparison of movement imagery ability self-report and imagery use in a motor task. *Journal of Imagery Research in Sport and Physical Activity, 9*(1), 61-66.

Gabbard, C., Ammar, D., & Rodrigues, L. (2005). Handedness effects on mentally stimulated reaching, . *Human Movement Science, 24*(4), 484-495.

Ganis, G., Keenan, J. P., Kosslyn, S. M., & Pascual-Leone, A. (2000). Transcranial magnetic stimulation of primary motor cortex affects mental rotation. *Cerebral Cortex (New York, N.Y.: 1991), 10*(2), 175-180.

Goodale, M. A., Pelisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature, 320*(6064), 748-750.

Hall, C. R., & Pongrac, J. (1983). Movement Imagery Questionnaire. Faculty of Physical Education. The University of Western Ontario, London, Ontario, Canada.

Harrell, F.E. (2001). *Regression Modeling Strategies, with Applications to Linear Models, Logistic Regression, and Survival Analysis.* New York, NY: Springer.

Hardy, L., & Callow, N. (1999). Efficacy of external and internal visual imagery perspectives for the enhancement of tasks in which form is important. *Journal of Sport & Exercise Psychology,* 21, 95-112.

Hyde, C., Fuelscher, I., Buckthought, K., Enticott, P. G., Gitay, M. A., & Williams, J. (2014). Motor imagery is less efficient in adults with probable developmental coordination disorder: Evidence from the hand rotation task. *Research in Developmental Disabilities, 35*(11), 3062-3070.

Hyde, C., & Wilson, P. (2011a). Online motor control in children with developmental coordination disorder: Chronometric analysis of double-step reaching performance. *Child: Care, Health and Development, 37*(1), 111-122.

Hyde, C., & Wilson, P. H. (2011b). Dissecting online control in developmental coordination disorder: A kinematic analysis of double-step reaching. *Brain and Cognition, 75*(3), 232-241.

Hyde, C., & Wilson, P. H. (2011). Dissecting online control in developmental coordination disorder: A kinematic analysis of double-step reaching. *Brain and Cognition, 75*(3), 232-241.

Hyde, C. E., & Wilson, P. H. (2013). Impaired online control in children with developmental coordination disorder reflects developmental immaturity. *Developmental Neuropsychology, 38*(2), 81-97.

Hyde, C., Wilmut, K., Fuelscher, I., & Williams, J. (2013). Does implicit motor imagery ability predict reaching correction efficiency? A test of recent models of human motor control. *Journal of Motor Behavior, 45*(3), 259-269.

Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *Neuroimage, 14*(1), S103-S109.

Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. New York, NY, USA: Oxford Press.

Lawrence, G., Callow, N., & Roberts, R. (2013). Watch me if you can: imagery ability moderates observational learning effectiveness. *Frontiers in Human Neuroscience*, *7*, 1-7.

Land, M. F., & McLeod, P. (2000). From eye movements to actions: How batsmen hit the ball. *Nature Neuroscience, 3*(12), 1340-1345.

Lequerica, A., Rapport, L., Axelrod, B.N., Telmet, K., & Whitman, R.D. (2002). Subjective and Objective Assessment Methods of Mental Imagery Control: Construct Validations of Self-Report Measures. *Journal of Clinical and Experimental Neuropsychology*, *24*(8), 1103-1116.

Martini, R., Carter, M. J., Yokon, E., Cumming, J., & Ste-Marie, D. M. (2016).

Development and validation of the movement imagery questionnaire for children (MIQ-C). *Psychology of Sport and Exercise, 22*, 190-201.

McLeod, P. (1987). Visual reaction time and high-speed ball games. *Perception, 16*(1), 49-59.

McAvinue, L. P., & Robertson, I. H. (2008). Measuring motor imagery ability: A review. *European Journal of Cognitive Psychology, 20*(2), 232-251.

McAvinue, L. P. & Robertson, I. H. (2009). Motor imagery: A multidimensional ability. *Journal of Mental Imagery, 33 (1&2),* 99-120.

Meltzoff, A.N., & Gopnik, A. (1993). The role of imitation in understanding persons and developing a theory of mind. In S. Baron-Cohen, H. Tager-Flusberg, & D.J. Cohen (Eds.), *Under .standing other minds: Perspectives from autism. New* Y ork: Oxford University Press.

Meltzoff, A. N., & Moore, M. K. (1994). Imitation, memory, and the representation of persons. *Infant Behaviour and Development, 17*, 93-99.

Molina, M., Tijus, C., & Jouen, F. (2008). The emergence of motor imagery in children. *Journal of Experimental Child Psychology, 99*(3), 196-209.

Munzert, J., Lorey, B., & Zentgraf, K. (2009). Cognitive motor processes: The role of motor imagery in the study of motor representations. *Brain Research Reviews, 60*(2), 306-326.

Munzert, J., & Zentgraf, K. (2009). Motor imagery and its implications for understanding the motor system. *Progress in Brain Research, 174*, 219-229.

Paillard, J. (1996) Fast and slow feedback loops for the visual correction of spatial errors in a pointing task: a re-appraisal. *Canadian Journal of Physiology and Pharmacology*. *74*, 401–417.

Pisella, L., Grea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: Toward reinterpreting optic ataxia. *Nature Neuroscience, 3*(7), 729-736.

Plumb, M. S., Wilson, A. D., Mulroue, A., Brockman, A., Williams, J. H., & Mon-Williams, M. (2008). Online corrections in children with and without DCD. *Human Movement Science, 27*(5), 695-704.

Qt Creator Version 3.1.0. (2014) The Qt Company. Retrieved from: http://www.qt.io/ide/

Ruddock, S. R., Hyde, C. E., Piek, J. P., Sugden, D., Morris, S., & Wilson, P. H. (2014). Executive systems constrain the flexibility of online control in children during goal-directed reaching. *Developmental Neuropsychology, 39*(1), 51-68.

Starkes, J. L. (1987). Skill in field hockey: The nature of the cognitive advantage. *Journal of Sports Psychology, 9*, 146-160.

Takeda, K., Shimoda, N., Sato, Y., Ogano, M., & Kato, H. (2009). Reaction time differences between left- and right-handers during mental rotation of hand pictures. *Laterality,* , 1-11.

ter Horst, A. C., van Lier, R., & Steenbergen, B. (2010). Mental rotation task of hands: Differential influence number of rotational axes. *Experimental Brain Research.Experimentelle Hirnforschung.Experimentation Cerebrale, 203*(2), 347-354.

Wang, Z., Meltzoff, A. N., & Williamson, R. A. (2015). Social learning promotes understanding of the physical world: Preschool children's imitation of weight sorting. *Journal of Experimental Child Psychology, 136*, 82-91.

White, A., & Hardy, L. (1995). Use of different imagery perspectives on the learning and performance of different motor skills. *British Journal of Psychology (London, England : 1953), 86 (Pt 2)*(Pt 2), 169-180.

Williams, J., Thomas, P. R., Maruff, P., & Wilson, P. H. (2008). The link between motor impairment level and motor imagery ability in children with developmental coordination disorder. *Human Movement Science, 27*(2), 270-285.

Williams, S. E., & Cumming, J. (2012). Athletes' ease of imaging predicts their imagery and observational learning use. *Psychology of Sport and Exercise, 13*, 363-370.

Williams, S. E., Cumming, J., Ntoumanis, N., Nordin-Bates, S. M., Ramsey, R., & Hall, C. (2012). Further validation and development of the movement imagery questionnaire. *Journal of Sport & Exercise Psychology, 34*(5), 621-646.

Williamson, R. A., Jaswal, V. K., & Meltzoff, A. N. (2010). Learning the rules: Observation and imitation of a sorting strategy by 36-month-old children. *Developmental Psychology, 46*(1), 57-65.

Wilson, P. H., & Hyde, C. (2013). The development of rapid online control in children aged 6-12 years: Reaching performance. *Human Movement Science, 32*(5), 1138-1150.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3 Suppl*, 1212.

Chapter III: General Discussion and Conclusion

Movement imagery ability has been positively related to motor performance in healthy adult populations (Gabbard & Bobbio, 2011; Gabbard et al., 2012; Hyde et al. 2013; Williams et al., 2008). Hyde et al. (2013) depicted this relationship empirically via hierarchal regression modeling and determined that movement imagery ability, as measured via a hand rotation task, accounted for 39% of the variance in the time required to make trajectory corrections during rapid reaching movements. The findings in Hyde et al. (2013) support the relationship between movement imagery and online control in healthy adults where both imagery and online control abilities are already fully developed. Studies have shown that in late childhood movement imagery ability and online control have been demonstrated to be undergoing rapid non-linear phases of development until they attain adult like levels around 12 years of age (Choudhury et al., 2007a/b, Gabbard, 2009; Gabbard & Bobbio, 2011). If the two processes are as closely linked as suggested by the Hyde et al. (2013) study, the observed relationship should hold true in late childhood as well.

The current study addressed the relationship between online control and movement imagery ability using both implicit (hand rotation task) and explicit (MIQ-C) movement imagery ability measures. The use of the hand rotation task allowed for a wholly objective measure of overall imagery ability, while the MIQ-C allowed us to quantify, subjectively, the movement imagery ability of the children from varying perspectives. With a greater degree of detail relating to movement imagery ability than used in previous studies, we were able to perform a hierarchal regression analysis on key variables of movement imagery ability, attained via the hand rotation task and the MIQ-

C, as predictors of online control, as measured via DSRT, in children ages 7-12. Our results revealed that the reaction time and accuracy of responses to medially rotated stimuli in the hand rotation task accounted for a significant amount of the variance observed in TTC, suggesting that the relationship between movement imagery ability and the ability to correct reaches online exists throughout development.

While a mental hand rotation task is a widely used objective measure of movement imagery ability (Hyde et al., 2013: Parsons, 1994; Takeda et al., 2009), it is widely suggested that movement imagery ability differs based on perspective (Hall et al., 1985; White & Hardy, 1995; Williams et al., 2012). As previously mentioned, while several measurement tools exist for differentiating movement imagery perspective, the current study utilized the MIQ-C (Martini et al., 2016), which is currently the only movement imagery tool to be validated for use with children. The secondary benefit to utilizing the MIQ-C as an alternative measure of movement imagery ability was that it allowed the inclusion of both an implicit and explicit measures of movement imagery in our models. Our study analyzed the data from the MIQ-C on their own as predictors of online control as well as in combination with the hand rotation task data to determine i) whether a particular perspective of movement imagery was a better predictor of online control and ii) whether a combination of both explicit and implicit measures of movement imagery is a better predictor of online control than either alone. Our results suggest that while on their own, the movement imagery scores failed to significantly predict online control, the external visual imagery perspective led to an improved model when paired with the medial stimulus variables from the hand rotation task, accounting for 55.9% of the variance in TTC. These findings suggest that the external visual imagery perspective is relevant to the mental representation of action theorized to be incorporated in online control processes (Desmurget & Grafton, 2000; Jordan & Rumelhart, 1992; Wolpert & Miall, 1996; Wolpert & Ghahramani, 2000; Wolpert et al. 2011). The fact that the model incorporating both explicit and implicit measures accounts for a greater proportion of the variance suggests that the depiction of movement imagery ability is incomplete when considered from either the hand rotation or the MIQ-C on their own. However, when considered together, they depict movement imagery ability more completely. This notion is supported by the previous work of Lequerica, Rapport, Axelrod, Telmet, & Whitman (2002), who compared multiple subjective and objective movement imagery measures, which included a hand rotation task and a previous version of the MIQ and found that results from subjective and objective assessment tools were unrelated. These authors suggest that this is due to a large portion of movement imagery measures failing to control the nature of the generated images or the strategies used to complete objective tasks. An example would be the lack of instruction on how specifically what steps a participant should follow to determine the laterality in a hand rotation task. This suggests that subjective and objective movement imagery measures provide information pertaining to different aspects of movement imagery, and thus, alone, each measure likely depicts one aspect of movement imagery ability and not the complete ability itself.

While the current findings provide further evidence of the relationship between movement imagery ability and online control, the study does have several limitations. A relationship between these two abilities does not necessarily imply that one process has a direct effect on the other, i.e. that a change in movement imagery ability will lead to a change in the speed of trajectory changes online. However, the current methodology could be utilized in conjunction with an existing intervention designed to improve either movement imagery ability or online control. Based on the current model, an intervention designed to address a deficit in movement imagery would likely have a positive effect on online control and vice versa. This would allow researchers to analyze the effect of the intervention on key variables associated with either ability, as well as determine whether the relationship between movement imagery ability and online control remains consistent post intervention. This data could be beneficial in the clinical setting, by determining whether these interventions should be used to treat individuals with motor control deficits.

A second limitation is related to the fact that several cognitive factors, such as attention and motivation, are associated with the age of participants and the tasks. It is clear based on the model that general reaching efficiency is a major factor in TTC in the online control task, as it accounted for 17.0% of the variance in TTC, once controlling for age. Attention and motivation also have an effect on performance in both the hand rotation task and DSRT. While both parental consent and child assent were attained from all participants, the motivation of participants is influenced by several factors, including but not limited to: interest in the study, willingness to miss a portion of their summer daycamp, comfort with the researcher, as well as whether their willingness to participate was influenced by the parents. These factors would also affect the level of attention during the 30-45 minute study session. Consequently, we have attempted to account for some of these factors by entering age as a covariate in our modeling equations. .

In summary, the results of the current study further support a relationship between movement imagery ability and online control by providing evidence of the existence of this relationship during childhood. Our results also suggest that both implicit and explicit movement imagery measures should be considered in conjunction to attain a more complete picture of an individual's movement imagery ability. As the first study to incorporate the MIQ-C as an explicit measure, our study was able to determine that the external visual imagery perspective was more closely associated with the rapid goal directed reaching movements involved in a DSRT, than either the internal imagery or kinesthetic perspectives. While these findings add to the literature regarding movement imagery and online control, future studies are required to focus on this relationship in populations with motor and/or cognitive impairments, for example individuals with DCD who were excluded from the current study. Should the relationship observed in the current study hold true, it would suggest further support for the relationship between mental representations of action utilized in online control processes as well as movement imagery and potentially suggest clinical implications.

References

Aflalo, T., Kellis, S., Klaes, C., Lee, B., Shi, Y., Pejsa, K., Shanfield, K., Hayes-Jackson, S., Aisen, M., Heck, C., Liu, C, & Andersen, R.A. (2015). Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. *Science. 308*, 906-910.

Andersen, R. A., & Cui, H. (2009). Intention, action planning, and decision making in parietal-frontal circuits. *Neuron, 63*(5), 568-583.

Battaglia, F., Quartarone, A., Ghilardi, M. A., Dattola, R., Bagnato, S., Rizzo, V., Morgante, L., & Girlanda, L. (2006). Unilateral cerebellar stroke disrupts movement preparation and motor imagery. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology. 117*(5), 1009-16.

Blangero, A., Menz, M. M., McNamara, A., & Binkofski, F. (2009). Parietal modules for reaching. *Neuropsychologia, 47*(6), 1500-1507.

Biguer, B., Jeannerod, M., & Prablanc, C. (1982). The coordination of eye, head, and arm movements during reaching at a single visual target. *Experimental Brain Research.Experimentelle Hirnforschung.Experimentation Cerebrale, 46*(2), 301-304.

Butson, M. L., Hyde, C., Steenbergen, B., & Williams, J. (2014). Assessing motor imagery using the hand rotation task: Does performance change across childhood? *Human Movement Science, 35*, 50-65.

Caeyenberghs, K., Wilson, P. H., van Roon, D., Swinnen, S. P., & Smits-Engelsman, B. C. (2009). Increasing convergence between imagined and executed movement across development: Evidence for the emergence of movement representations. *Developmental Science, 12*(3), 474-483.

Castiello, U., Paulignan, Y., & Jeannerod, M. (1991). Temporal dissociation of motor responses and subjective awareness. A study in normal subjects. *Brain : A Journal of Neurology, 114 (Pt 6)*(Pt 6), 2639-2655.

Choudhury, S., Charman, T., Bird, V., & Blakemore, S. J. (2007). Adolescent development of motor imagery in a visually guided pointing task. *Consciousness and Cognition, 16*(4), 886-896.

Choudhury, S., Charman, T., Bird, V., & Blakemore, S. J. (2007). Development of action representation during adolescence. *Neuropsychologia, 45*(2), 255-262.

Clower, D. M., Hoffman, J. M., Votaw, J. R., Faber, T. L., Woods, R. P., & Alexander, G. E. (1996). Role of posterior parietal cortex in the recalibration of visually guided reaching. *Nature, 383*(6601), 618-621.

Cressman, E. K., Franks, I. M., Enns, J. T., & Chua, R. (2006). No automatic pilot for visually guided aiming based on colour. *Experimental Brain Research, 171*(2), 174-183.

Cressman, E.K., Cameron, B.D., Lam, M.Y., Franks, I.M., & Chua, R. (2010). Movement duration does not affect automatic online control. *Human Movement Science. 29*, 871-881.

Cunnington, R., Egan, G. F., O'Sullivan, J. D., Hughes, A. J., Bradshaw, J. L. & Colebatch, J. G. (2001). Motor imagery in Parkinson's disease: A PET study. *Movement Disorders. 16*, 849–857.

de Lange, F. P., Helmich, R. C., & Toni, I. (2006). Posture influences motor imagery: An fMRI study. *Neuroimage, 33*(2), 609-617.

Decety, J. (1991). Motor information may be important for updating the cognitive processes involved in mental imagery of movement. *European Bulletin of Cognitive Psychology, 4*, 415-426.

Decety, J. (1996). Do imagined and executed actions share the same neural substrate? *Brain Research.Cognitive Brain Research, 3*(2), 87-93.

Decety, J., & Jeannerod, M. (1995). Mentally simulated movements in virtual reality: Does fitts's law hold in motor imagery? *Behavioural Brain Research, 72*(1-2), 127-134.

Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioural Brain Research, 34*(1-2), 35-42.

Desmurget, M., Epstein, C. M., Turner, R. S., Prablanc, C., Alexander, G. E., & Grafton, S. T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience, 2*(6), 563-567.

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences, 4*(11), 423-431.

Desmurget, M., Turner, R. S., Prablanc, C., Russo, G. S., Alexander, G. E., & Grafton, S. T. (2005). Updating target location at the end of an orienting saccade affects the characteristics of simple point-to-point movements. *Journal of Experimental Psychology.Human Perception and Performance, 31*(6), 1510-1536.

Dey, A., Barnsley, N., Mohan, R., McCormick, M., McAuley, J. H., & Moseley, G. L. (2012). Are children who play a sport or a musical instrument better at motor imagery than children who do not?. *British Journal Of Sports Medicine*, *46*(13), 923-926.

Elliott, D., Hansen, S., & Grierson, L. E. (2009). Optimising speed and energy expenditure in accurate visually directed upper limb movements. *Ergonomics,* *52*(4), 438-447.

Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior, 36*(3), 339-351.

Epstein, D. (2013). *The sports gene: inside the science of extraordinary athletic performance*. New York, New York, U.S.A.: Penguin Group.

Farne, A., Roy, A. C., Paulignan, Y., Rode, G., Rossetti, Y., Boisson, D., & Jeannerod, M. (2003). Visuo-motor control of the ipsilateral hand: Evidence from right brain-damaged patients. *Neuropsychologia, 41*(6), 739-757.

Ferster, D. (1996). Is neural noise just a nuisance?. *Science. 273*, 1812

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*, 402–408.

Gabbard, C. (2009). Studying action representation in children via motor imagery. *Brain and Cognition, 71*(3), 234-239.

Gabbard, C., & Bobbio, T. (2011). The inability to mentally represent action may be associated with performance deficits in children with developmental coordination disorder. *The International Journal of Neuroscience, 121*(3), 113-120.

Gabbard, C., Cacola, P., & Bobbio, T. (2012). The ability to mentally represent action is associated with low motor ability in children: A preliminary investigation. *Child: Care, Health and Development, 38*(3), 390-393.

Gabbard, C., Cordova, A., & Ammar, D. (2007). Estimation of reach in peripersonal and extrapersonal space: A developmental view. *Developmental Neuropsychology, 32*(3), 749-756.

Gabbard, C., & Lee, J. (2014). A comparison of movement imagery ability self-report and imagery use in a motor task. *Journal of Imagery Research in Sport and Physical Activity, 9*(1), 61-66.

Ganis, G., Keenan, J. P., Kosslyn, S. M., & Pascual-Leone, A. (2000). Transcranial magnetic stimulation of primary motor cortex affects mental rotation. *Cerebral Cortex (New York, N.Y.: 1991), 10*(2), 175-180.

Gaveau, V., Pisella, L., Priot, A., Fukui, T., Rossetti, Y., Pelisson, D., & Prablanc, C. (2014). Automatic online control of motor adjustments in reaching and grasping. *Neuropsychologia. 55*, 25-40.

Godaux, E., Koulischer, D., & Jacquy, J. (1992). Parkinsonian bradykinesia is due to depression in the rate of rise of muscle activity. *Annals of Neurology, 31*(1), 93-100.

Goodale, M. A., Pelisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature, 320*(6064), 748-750.

Grush, R. (2004). The emulation theory of representation: Motor control, imagery and perception. *Behavioral and Brain Sciences. 27*, 377-396.

Hall, C. R., & Martin, K. A. (1997). Measuring movement imagery abilities: A revision of the Movement Imagery Questionnaire. *Journal of Mental Imagery, 21*, 143–154.

Hall, C. R., Pongrac, J. (1983). Movement Imagery Questionnaire. Faculty of Physical Education. The University of Western Ontario, London, Ontario, Canada. Ontario.

Hall, C. R., Pongrac, J., & Buckloz, E. (1985). The measurement of imagery ability. *Human Movement Science, 4,* 107–118.

Harrell, F.E. (2001). *Regression Modeling Strategies, with Applications to Linear Models, Logistic Regression, and Survival Analysis.* New York, NY: Springer.

Hardy, L., & Callow, N. (1999). Efficacy of external and internal visual imagery perspectives for the enhancement of tasks in which form is important. *Journal of Sport & Exercise Psychology,* 21, 95-112.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature, 394*(6695), 780-784.

Heremans, E., Helsen, W. F., & Feys, P. (2008). The eyes as a mirror of our thoughts: quantification of motor imagery through eye movement registration. *Behavioral Brain Research. 187*, 351-360.

Hyde, C., Fuelscher, I., Buckthought, K., Enticott, P. G., Gitay, M. A., & Williams, J. (2014). Motor imagery is less efficient in adults with probable developmental coordination disorder: Evidence from the hand rotation task. *Research in Developmental Disabilities, 35*(11), 3062-3070.

Hyde, C., Wilmut, K., Fuelscher, I., & Williams, J. (2013). Does implicit motor imagery ability predict reaching correction efficiency? A test of recent models of human motor control. *Journal of Motor Behavior, 45*(3), 259-269.

Hyde, C., & Wilson, P. (2011). Online motor control in children with developmental coordination disorder: Chronometric analysis of double-step reaching performance. *Child: Care, Health and Development, 37*(1), 111-122.

Hyde, C., & Wilson, P. H. (2011). Dissecting online control in developmental coordination disorder: A kinematic analysis of double-step reaching. *Brain and Cognition, 75*(3), 232-241.

Hyde, C. E., & Wilson, P. H. (2013). Impaired online control in children with developmental coordination disorder reflects developmental immaturity. *Developmental Neuropsychology, 38*(2), 81-97.

Isaac, A. R., & Marks, D. F. (1994). Individual differences in mental imagery experience: developmental changes and specialization. *British Journal of Psychology, 85*, 479-500.

Isaac, A., Marks, D. F., & Russell, D. G. (1986) An instrument for assessing imagery of movement: the vividness of movement imagery questionnaire (VMIQ). *Journal of Mental Imagery, 10*. 23–30.

Jeannerod, M. (1997). *The cognitive neuroscience of action*. Oxford, UK: Blackwell Publishers.

Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *Neuroimage, 14*(1), S103-S109.

Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. New York, NY, USA: Oxford Press.

Johnson, M. H. (2011). Interactive specialization: A domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience, 1*(1), 7-21.

Jordan, M. I., & Rumelhart, D. E. (1992). Forward models—supervised learning with a distal teacher. *Cogn. Sci. 16*, 307–354.

King, B. R., Oliveira, M. A., Contreras-Vidal, J. L., & Clark, J. E. (2012). Development of state estimation explains improvements in sensorimotor performance across childhood. *Journal of Neurophysiology, 107*(11), 3040-3049.

Kosslyn, S. M., Margolis, J. A., Barrett, A. M., Goldknopf, E. J., & Daly, P. F. (1990). Age differences in imagery abilities. *Child Development, 61*(4), 995-1010.

Lawrence, G., Callow, N., & Roberts, R. (2013). Watch me if you can: imagery ability moderates observational learning effectiveness. *Frontiers in Human Neuroscience, 7*, 1-7.

Land, M. F., & McLeod, P. (2000). From eye movements to actions: How batsmen hit the ball. *Nature Neuroscience, 3*(12), 1340-1345.

Lequerica, A., Rapport, L., Axelrod, B.N., Telmet, K., & Whitman, R.D. (2002). Subjective and Objective Assessment Methods of Mental Imagery Control: Construct Validations of Self-Report Measures. *Journal of Clinical and Experimental Neuropsychology*, *24*(8), 1103-1116.

Lorant, J., & Nicholas, A. (2004). Validation de la traduction Française du Movement Imagery Questionnaire-Revised (MIQ-R). *Science & Motricite, 53,* 57–68.

Magescas, F., Urquizar, C., & Prablanc, C. (2009). Two modes of error processing in reaching. *Experimental Brain Research, 193,* 337–350.

Martini, R., Carter, M. J., Yoxon, E., Cummings, J., & Ste-Marie, D. M. (in preparation). Development and validation of the Movement Imagery Questionnaire for Children (MIQ-C).

McAvinue, L. P., & Robertson, I. H. (2008). Measuring motor imagery ability: A review. *European Journal of Cognitive Psychology, 20*(2), 232-251.

McAvinue, L. P. & Robertson, I. H. (2009). Motor imagery: A multidimensional ability. *Journal of Mental Imagery, 33 (1&2),* 99-120.

McIntosh, R. D., Mulroue, A., & Brockmole, J. R. (2010). How automatic is the hand's automatic pilot? *Experimental Brain Research*, *206*(3), 257–269.

McLeod, P. (1987). Visual reaction time and high-speed ball games. *Perception, 16*(1), 49-59.

Meltzoff, A.N., & Gopnik, A. (1993). The role of imitation in understanding persons and developing a theory of mind. In S. Baron-Cohen, H. Tager-Flusberg, & D.J. Cohen (Eds.), *Under .standing other minds: Perspectives from autism. New* Y ork: Oxford University Press.

Meltzoff, A. N., & Moore, M. K. (1994). Imitation, memory, and the representation of persons. *Infant Behaviour and Development, 17*, 93-99.

Molina, M., Tijus, C., & Jouen, F. (2008). The emergence of motor imagery in children. *Journal of Experimental Child Psychology, 99*(3), 196-209.

Munzert, J., Lorey, B., & Zentgraf, K. (2009). Cognitive motor processes: The role of motor imagery in the study of motor representations. *Brain Research Reviews, 60*(2), 306-326.

Munzert, J., & Zentgraf, K. (2009). Motor imagery and its implications for understanding the motor system. *Progress in Brain Research, 174*, 219-229.

Osu, R., Morishige, K., Miyamoto, H., & Kawato, M. (2009). Feedforward impedance control efficiently reduce motor variability. *Neuroscience Research. 65*, 6-10.

Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology.Human Perception and Performance, 20*(4), 709-730.

Pisella, L., Grea, H., Tilikete, C., Vighetto, A., Desmurget, M., Rode, G., Boisson, D., Rossetti, Y. (2000). An 'automatic pilot' for the hand in human posterior parietal cortex: Toward reinterpreting optic ataxia. *Nature Neuroscience, 3*(7), 729-736.

Plumb, M. S., Wilson, A. D., Mulroue, A., Brockman, A., Williams, J. H., & Mon-Williams, M. (2008). Online corrections in children with and without DCD. *Human Movement Science, 27*(5), 695-704.

Prablanc, C., & Martin, O. (1992). Automatic control during hand reaching at undetected two-dimensional target displacements. J*ournal of Neurophysiology, 67*, 455–469.

Qt Creator Version 3.1.0. (2014) The Qt Company. Retrieved from: http://www.qt.io/ide/

Reichenbach, A., Bresciani, J. P., Peer, A., Bulthoff, H. H., & Thielscher, A. (2011). Contributions of the PPC to online control of visually guided reaching movements assessed with fMRI-guided TMS. *Cerebral Cortex (New York, N.Y.: 1991), 21*(7), 1602-1612.

Roberts, R., Callow, N., Hardy, L., Markland, D., & Bringer, J. (2008). Movement imagery ability e development and assessment of a revised version of vividness of movement imagery Questionnaire. *Journal of Sport & Exercise Psychology. 30*, 200-221.

Ruddock, S. R., Hyde, C. E., Piek, J. P., Sugden, D., Morris, S., & Wilson, P. H. (2014). Executive systems constrain the flexibility of online control in children during goal-directed reaching. *Developmental Neuropsychology, 39*(1), 51-68.

Sarlegna, F. R. (2006). Impairment of online control of reaching movements with aging: A double-step study. *Neuroscience Letters, 403*(3), 309-314.

Skoura, X., Vinter, A., & Papaxanthis, C. (2009). Mentally simulated motor actions in children. *Developmental Neuropsychology, 34*(3), 356-367.

Starkes, J. L. (1987). Skill in field hockey: The nature of the cognitive advantage. *Journal of Sports Psychology, 9*, 146-160.

Takeda, K., Shimoda, N., Sato, Y., Ogano, M., & Kato, H. (2009). Reaction time differences between left- and right-handers during mental rotation of hand pictures. *Laterality,* , 1-11.

Taktek, K., Zinsser, N., & St John, B. (2008). Visual versus kinesthetic mental imagery: efficacy for the retention and transfer of a closed motor skill in young children. *Journal of Experimental Psychology, 62*(3), 174-187.

Van Braeckel, K., Butcher, P. R., Geuze, R. H., Stremmelaar, E. F., & Bouma, A. (2007). Movement adaptations in 7- to 10-year-old typically developing children: Evidence for a transition in feedback-based motor control. *Human Movement Science*. *26*(6), 927–942.

Wang, Z., Meltzoff, A. N., & Williamson, R. A. (2015). Social learning promotes understanding of the physical world: Preschool children's imitation of weight sorting. *Journal of Experimental Child Psychology, 136*, 82-91.

White, A., & Hardy, L. (1995). Use of different imagery perspectives on the learning and performance of different motor skills. *British Journal of Psychology (London, England : 1953), 86 (Pt 2)*(Pt 2), 169-180.

Williams, J., Thomas, P. R., Maruff, P., & Wilson, P. H. (2008). The link between motor impairment level and motor imagery ability in children with developmental coordination disorder. *Human Movement Science, 27*(2), 270-285.

Williams, J., Omizzolo, C., Galea, M. P., & Vance, A. (2013). Motor imagery skills of children with Attention Deficit Hyperactivity Disorder and Developmental Coordination Disorder. *Human Movement Science, 32*(1), 121-135.

Williams, S. E., & Cumming, J. (2012). Athletes' ease of imaging predicts their imagery and observational learning use. *Psychology of Sport and Exercise, 13*, 363-370.

Williams, S. E., Cumming, J., Ntoumanis, N., Nordin-Bates, S. M., Ramsey, R., & Hall, C. (2012). Further validation and development of the movement imagery questionnaire. *Journal of Sport & Exercise Psychology, 34*(5), 621-646.

Williamson, R. A., Jaswal, V. K., & Meltzoff, A. N. (2010). Learning the rules: Observation and imitation of a sorting strategy by 36-month-old children. *Developmental Psychology, 46*(1), 57-65.

Wilson, P. H., & Hyde, C. (2013). The development of rapid online control in children aged 6-12 years: Reaching performance. *Human Movement Science, 32*(5), 1138-1150.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3 Suppl*, 1212.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews.Neuroscience, 12*(12), 739-751.

Wolpert, D. M., & Miall, R. C. (1996). Forward models for physiological motor control. *Neural Networks : The Official Journal of the International Neural Network Society, 9*(8), 1265-1279.

Wolpert, D. M., Miall, R. C., & Kawato, M. (1998). Internal models in the cerebellum. *Trends in Cognitive Sciences, 2*(9), 338-347.

Appendix A

File Number: H05-14-14 **Date (mm/dd/yyyy):** 06/09/2014

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Rose	Martini	Health Sciences / Occupational Therapy	Supervisor
Marcus	Sooley	Health Sciences / Human Kinetics	Student Researcher

File Number: H05-14-14

Type of Project: Master's Thesis

Title: The relationship between movement imagery and online control ability in typically developing children

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
06/09/2014	06/08/2015	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A

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Appendix B

Edinburgh Handedness Inventory – Short Form

Please indicate your preferences in the use of hands in the following activities or objects:

	Always right	Usually right	Both equally	Usually left	Always left
Writing	☐	☐	☐	☐	☐
Throwing	☐	☐	☐	☐	☐
Toothbrush	☐	☐	☐	☐	☐
Spoon	☐	☐	☐	☐	☐

Appendix C

DSRT calgary health region Alberta Children's HOSPITAL FOUNDATION FACULTY OF MEDICINE | UNIVERSITY OF CALGARY

COORDINATION QUESTIONNAIRE (REVISED 2007)

Name of Child: ______________________ **Today's Date:**

Person completing Questionnaire: ______________________ **Birth Date:**

Relationship to child: ______________________ **Child's Age:**

	Year	Mon	Day
Today's Date:			
Birth Date:			
Child's Age:			

Most of the motor skills that this questionnaire asks about are things that your child does with his or her hands, or when moving.
A child's coordination may improve each year as they grow and develop. For this reason, it will be easier for you to answer the questions if you think about other children that you know who ***are the same age as your child***.
Please compare the degree of coordination your child has with other children of the same age when answering the questions.
Circle the one number that best describes your child. If you change your answer and want to circle another number, please circle the correct response twice.
If you are unclear about the meaning of a question, or about how you would answer a question to best describe your child, please call________________________ at ________________ for assistance.

Not at all like your child	A bit like your child	Moderately like your child	Quite a bit like your child	Extremely like your child
1	**2**	**3**	**4**	**5**

1. Your child *throws a ball* in a controlled and accurate fashion.

   1 2 3 4 5

2. Your child *catches* a small *ball* (e.g., tennis ball size) thrown from a distance of 6 to 8 feet (1.8 to 2.4 meters).

   1 2 3 4 5

3. Your child *hits* an approaching *ball* or *birdie* with a bat or racquet accurately.

   1 2 3 4 5

4. Your child *jumps* easily *over* obstacles found in garden or play environment.

   1 2 3 4 5

5. Your child *runs* as fast and in a *similar* way to other children of the same gender and age.

   1 2 3 4 5

6. If your child has a *plan* to do a motor *activity*, he/she can organize his/her body to follow the plan and effectively complete the task (e.g., building a cardboard or cushion "fort," moving on playground equipment, building a house or a structure with blocks, or using craft materials).

   1 2 3 4 5

(OVER)

Decision Support Research Team
Alberta Children's Hospital
2888 Shaganappi Trail NW, Calgary, AB, Canada T3B 6A8
www.calgaryhealthregion.ca/dsrt/dcdq.htm
1

	Not at all like your child 1	A bit like your child 2	Moderately like your child 3	Quite a bit like your child 4	Extremely like your child 5

7. Your child's printing or *writing* or drawing in class is *fast* enough to keep up with the rest of the children in the class.

   1 2 3 4 5

8. Your child's printing or *writing* letters, numbers and words is *legible*, precise and accurate or, if your child is not yet printing, he or she *colors and draws* in a coordinated way and makes pictures that you can recognize.

   1 2 3 4 5

9. Your child uses appropriate *effort* or tension when printing or writing or drawing (no excessive *pressure* or tightness of grasp on the pencil, writing is not too heavy or dark, or too light).

   1 2 3 4 5

10. Your child *cuts* out pictures and *shapes* accurately and easily.

   1 2 3 4 5

11. Your child is interested in and *likes* participating in *sports or active* games requiring good motor skills.

   1 2 3 4 5

12. Your child learns *new motor tasks* (e.g., swimming, rollerblading) easily and does not require more practice or time than other children to achieve the same level of skill.

   1 2 3 4 5

13. Your child is *quick and competent* in tidying up, putting on shoes, tying shoes, dressing, etc.

   1 2 3 4 5

14. Your child would ***never*** be described as a *"bull in a china shop"* (that is, appears so clumsy that he or she might break fragile things in a small room).

   1 2 3 4 5

15. Your child does ***not*** *fatigue easily* or appear to slouch and "fall out" of the chair if required to sit for long periods.

   1 2 3 4 5

Thank you.

Decision Support Research Team
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DSRT calgary health region Alberta Children's Hospital Foundation Faculty of Medicine | University of Calgary

COORDINATION QUESTIONNAIRE (DCDQ'07): SCORE SHEET

Name: ______________________ **Date:** ____________

Birth Date: ______________________ **Age:** ____________

	Control During Movement	Fine Motor/ Handwriting	General Coordination
1. Throws ball			
2. Catches ball			
3. Hits ball/birdie			
4. Jumps over			
5. Runs			
6. Plans activity			
7. Writing fast			
8. Writing legibly			
9. Effort and pressure			
10. Cuts			
11. Likes sports			
12. Learning new skills			
13. Quick and competent			
14. "Bull in shop"			
15. Does not fatigue			

TOTAL ____ / 30 Control during Movement + ____ / 20 Fine Motor/ Handwriting + ____ / 25 General Coordination = ____ / 75 **TOTAL**

For Children Ages 5 years 0 months to 7 years 11 months

15-46 indication of DCD or suspect DCD
47-75 probably not DCD

For Children Ages 8 years 0 months to 9 years 11 months

15-55 indication of DCD or suspect DCD
56-75 probably not DCD

For Children Ages 10 years 0 months to 15 years

15-57 indication of DCD or suspect DCD
58-75 probably not DCD

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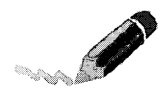
www.calgaryhealthregion.ca/dsrt/dcdq.htm

Appendix D

QUESTIONNAIRE SUR LE TROUBLE DE L'AQUISITION DE LA COORDINATION (QTAC)
©Martini, R, St-Pierre, M-F et Wilson, BN

Developmental Coordination Disorder Questionnaire-French Canadian (DCDQ-FC)
(basé sur le DCDQ'07)
©B.N. Wilson 2007

Questionnaire sur la coordination



Année	Mois	Jour

Nom de l'enfant : ______________________ Date (aujourd'hui):

Personne répondant au questionnaire : ______________________ Date de naissance de l'enfant :

Lien avec l'enfant : ______________________ Âge de l'enfant :

La plupart des habiletés motrices abordées dans ce questionnaire sont des choses que votre enfant fait avec ses mains ou lorsqu'il/elle est en mouvement. La coordination d'un enfant peut s'améliorer à chaque année pendant sa croissance et son développement. Pour cette raison, il sera plus facile pour vous de répondre aux questions si vous pensez à d'autres enfants que vous connaissez qui ont le même âge que votre enfant.
Veuillez comparer le degré de coordination de votre enfant à celui d'autres enfants du même âge, lorsque vous répondez aux questions.
Encerclez le chiffre qui décrit le mieux votre enfant. Si vous changez votre réponse et voulez encercler un autre chiffre, veuillez encercler la bonne réponse deux fois.
Si le sens d'une question ne semble pas clair ou si vous ne trouvez pas la réponse qui décrit le mieux votre enfant, veuillez communiquer avec ____________________ au ______________ pour obtenir de l'aide.

Pas du tout semblable à votre enfant	Un peu semblable à votre enfant	Plus ou moins semblable à votre enfant	Très semblable à votre enfant	Extrêmement semblable à votre enfant
1	2	3	4	5

1. Votre enfant *lance une balle* d'une manière contrôlée et précise.

   1 2 3 4 5

2. Votre enfant *attrape* une petite *balle* (par exemple : de la taille d'une balle de tennis) lancée à partir d'une distance de six à huit pieds (1,8 à 2,4 mètres).

   1 2 3 4 5

3. Votre enfant *frappe* avec précision une *balle* ou un *volant de badminton* lancé dans sa direction avec un bâton ou une raquette.

   1 2 3 4 5

4. Votre enfant saute facilement par-dessus des obstacles se trouvant dans une cour ou un espace de jeu.

   1 2 3 4 5

5. Votre enfant court aussi vite que les autres enfants du même sexe et du même âge et cela d'une manière semblable.

   1 2 3 4 5

	Pas du tout semblable à votre enfant 1	Un peu semblable à votre enfant 2	Plus ou moins semblable à votre enfant 3	Très semblable à votre enfant 4	Extrêmement semblable à votre enfant 5

6. Si votre enfant a le projet de faire une *activité motrice*, il/elle peut organiser son corps afin de suivre son plan et réalise efficacement la tâche (par exemple : construire un « fort » en carton ou avec des coussins, se déplacer sur les installations d'un terrain de jeu, bâtir une maison ou une structure avec des blocs ou utiliser du matériel de bricolage).

1 2 3 4 5

7. Votre enfant *écrit* en lettres moulées ou en lettres attachées ou dessine assez *rapidement* pour suivre le rythme des autres enfants de sa classe.

1 2 3 4 5

8. Votre enfant *écrit* des lettres, des chiffres et des mots lisiblement, précisément et correctement soit en lettres moulées ou attachées ou, si votre enfant ne sait pas encore écrire, il/elle *colore* et *dessine* de façon coordonnée et fait des dessins que vous pouvez reconnaître.

1 2 3 4 5

9. Lorsque votre enfant écrit en lettres moulées ou attachées ou lorsque qu'il/elle dessine, il/elle fournit la tension ou l'*effort* approprié (aucune *pression* ou force excessive dans la prise du crayon, et son écriture n'est pas trop appuyée, trop foncée ou trop pâle).

1 2 3 4 5

10. Votre enfant *découpe* des images ou des *formes* avec précision et facilité.

1 2 3 4 5

11. Votre enfant s'intéresse aux *sports ou jeux actifs* qui exigent de bonnes habiletés motrices et *aime* y participer.

1 2 3 4 5

12. Votre enfant apprend facilement de *nouvelles tâches motrices* (par exemple : natation, patin à roues alignées) et n'a pas besoin de s'exercer davantage ou plus longtemps que les autres enfants pour atteindre le même niveau d'habileté.

1 2 3 4 5

13. Votre enfant est *rapide et efficace* lorsqu'il/elle range ses choses, met ses souliers, attache ses souliers, s'habille, etc.

1 2 3 4 5

14. On ne décrirait **jamais** votre enfant comme un « *éléphant dans un magasin de porcelaine* » (c'est-à-dire si maladroit qu'il pourrait briser des objets fragiles se trouvant dans une petite pièce).

1 2 3 4 5

15. Votre enfant ne se *fatigue* ***pas*** *facilement* ou ne semble pas s'affaisser et « tomber » de sa chaise s'il/elle doit demeurer assis(e) pendant de longues périodes.

1 2 3 4 5

Merci.

Appendix E

Université d'Ottawa | University of Ottawa

Faculté des sciences de la santé | Faculty of Health Sciences

uOttawa

Instructions

We want to know about three ways that movements can happen in your head.

First, we will ask you to do a movement. Then, we will ask you to do one of three things in your head, without moving any part of your body.

Before we get started, we will use words and pictures to help you understand the three things we will ask you to do. Anytime you do not understand anything, just ask me.

Let's use kicking a soccer ball as an example. Do you know what I mean by kicking a soccer ball?
(*Note to administrator: Ensure child understands movement)*

Now imagine in your head that you are kicking a soccer ball. Which picture would you choose if I asked you to see the movement of kicking the soccer ball, through your own eyes, as you are kicking?
(*Note to administrator: Let child choose picture and if incorrect picture is selected, explain)*
So, sometimes we will ask you to see the movement in your head as if you were seeing it through your own eyes; like in this picture.

Again, imagine in your head that you are kicking a soccer ball. But this time, I am asking you to see yourself kicking the soccer ball as if you were watching yourself on a video. Now which picture would you choose?
(*Note to administrator: Let child choose picture and if incorrect picture is selected, explain)*
So, sometimes we will ask you to see the movement in your head as if you were seeing yourself on a video, like in this picture.
(*Note to administrator: Leave pictures in view of the participant for the remainder of the testing session)*

Sometimes we will also want to know if you can *feel* the movement in your head, as if the muscles in your body were really doing the movement, even though you are not moving. So if I ask you about the muscles and body parts you might feel in your head when you imagine kicking a ball, what would they be?
(Note to administrator: Ensure child understands what is meant by 'feeling' the movement. Have child describe the sensation and guide the child if needed so that s/he understands)

We want to know how hard or how easy it is for you to see or feel different movements in your head. Now, there is no right or wrong answer, just answer the best you can about how you see or feel the movement in your head.

You will use this scale (*show scale*), to tell me about how easy or hard it was to see or feel the movements in your head. The scale goes from very hard / hard / kinda hard / not easy nor hard / kinda easy / easy / very easy.
(*Note to administrator: point to numbers on scale while reading choices)*

Before we start, let's make sure you understand how the scale works:
(*Note to administrator: Refer to pictures of glasses of water and scales. Leave scale in view of the participant for the remainder of the testing session)*

If you had a glass full of mud in front of you, like the one in this picture, and you were looking through this glass to see yourself kicking the ball…how hard or easy would it be for you to see yourself kicking the soccer ball? Which number on the scale would that be?
(Note to administrator: Have child point to their answer on the scale)

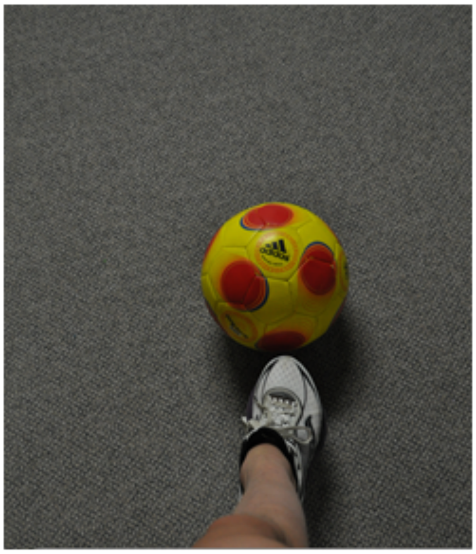
If the glass was full of cloudy water in front of you, like the one in this picture, and you were looking through it…how hard or how easy would it be for you to see yourself kicking the soccer ball? Which number on the scale would that be?
(Note to administrator: Have child point to their answer on the scale)

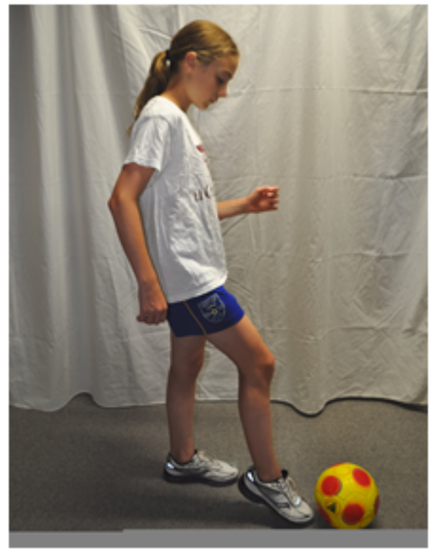
If the glass was empty and clean, like the one in this picture, and you were looking through it… how hard or how easy would it be for you to see yourself kicking the soccer ball? Which number on the scale would that be?
(Note to administrator: Have child point to their answer on the scale)

This scale will also be used to tell us how easy or hard it is for you to feel movements in your head without doing the movement.

Now I want you to imagine yourself kicking a soccer ball. Now, using the scale, tell me how hard or how easy it was to feel this movement in your head.
(Note to administrator: Have child point to their answer on the scale)

Now we will begin the actual questionnaire. I am going to read out a movement description to you and on the first time you are going to do the movement. I will then ask you to get into the starting position a second time but this time, to only imagine the movement. You will perform 4 different movements, 3 times each. Do you have any questions before we get started?





1	**2**	**3**	**4**	**5**	**6**	**7**
Very Hard	Hard	Kind of Hard	Not Easy nor Hard	Kind of Easy	Easy	Very Easy

ITEMS:

1. Starting position for this action is:

   Stand with your feet and legs close together and your arms at your sides.

   The movement to do is:
   Lift your right knee as high as you can. Bring it back down slowly until your two feet are on the ground. Make sure you do it slowly.

   Get into the starting position (*ask child if s/he remembers what that is)*

   In your head:
   Try feeling the knee lifting movement you just did, as if you were actually doing it, but without moving any part of your body.
   Was feeling this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

   Rating:

2. The starting position for this action is:

   Stand with your feet and legs close together and your arms at your sides

   The movement to do is:
   Bend down low and then jump in the air as high as you can, with your arms up over your head. Land with your feet apart and bring your arms back down.

   Get into the starting position. (*Ensure child remembers what that is)*

   In your head:
   Try to see the jumping movement you just did through your own eyes, like what you would see if you were actually doing it.
   Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

   Rating:

3. The starting position for this action is:

   Which arm do you write with? Now take the other arm and stretch it out to your side so the palm of your hand is facing the floor.

   The movement to do is:
   Keep your arm stretched out, and move it from your side to in front of you. Do this slowly.

   Get into the starting position. (*Ensure child remembers what that is)*

   In your head:
   Try to see the movement you just did of your arm moving to the front, as if you were watching yourself on video.
   Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

4. The starting position for this action is:

Stand with your feet apart and your arms stretched out all the way above your head.

The movement to do is:
Slowly bend your body forward and try to touch your toes with your fingertips. Now, stand back up with your arms above your head.

Get into starting position. (*Ensure child remembers what that is)*

In your head:
Try feeling the bending movement you just did, as if you were actually doing it, but without moving any part of your body.
Was feeling this very hard, hard, a kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

5. The starting position for this action is:

Stand with your feet and legs close together and your arms at your sides

The movement to do is:
Lift your right knee as high as you can. Bring it back down slowly until your two feet are on the ground. Make sure you do it slowly

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the knee lifting movement you just did through your own eyes, like what you would see if you were actually doing it.
Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

6. The starting position for this movement is:

Stand with your feet and legs close together and your arms at your sides

The movement to do is:
Bend down low and then jump in the air as high as you can, with your arms up over your head. Land with your feet apart and bring your arms back down.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the jumping movement you just did as if you were watching yourself on video.
Was seeing this very hard, hard, a bit hard, not easy and not hard, a bit easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

7. The starting position for this action is:
Take the arm that you do not write with, and stretch it out to your side so the palm of your hand is facing the floor.

The movement to do is:
Keep your arm stretched out, and move it from your side to in front of you. Do this slowly.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to feel the movement you just did of your arm moving to the front, as if you were actually doing it, but without moving any part of your body.
Was feeling this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

8. The starting position for this action is:
Stand with your feet apart and your arms stretched out all the way above your head.

The movement to do is:
Slowly bend your body forward and try to touch your toes with your fingertips. Now, stand back up with your arms above your head.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the bending movement you just did through your own eyes, like what you would see if you were actually doing it.
Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

9. The starting position for this action is:
Stand with your feet and legs close together and your arms at your sides

The movement to do is:
Lift your right knee as high as you can. Bring it back down slowly until your two feet are on the ground. Make sure you do it slowly

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the knee lifting movement you just did as if you were watching yourself on video.
Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

10. The starting position for this action is:
Stand with your feet and legs close together and your arms at your sides

The movement to do is:
Bend down low and then jump in the air as high as you can, with your arms up over your head. Land with your feet apart and bring your arms back down.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try feeling the jumping movement you just did, as if you were actually doing it, but without moving any part of your body.
Was feeling this very hard, hard, a kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

11. The starting position for this action is:
Take the arm that you do not write with, and stretch it out to your side so the palm of your hand is facing the floor.

The movement to do is:
Keep your arm stretched out, and move it from your side to in front of you. Do this slowly.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the movement you just did of your arm moving toward the front through your own eyes, like what you would see if you were actually doing it. Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

12. The starting position for this action is:
Stand with your feet apart and your arms stretched out all the way above your head.

The movement to do is:
Slowly bend your body forward and try to touch your toes with your fingertips. Now, stand back up with your arms above your head.

Get into the starting position. (*Ensure child remembers what that is)*

In your head:
Try to see the bending movement you just did as if you were watching yourself on video.
Was seeing this very hard, hard, kind of hard, not easy nor hard, kind of easy, easy or very easy? (*Note to administrator: point to numbers while reading choices)*

Rating:

Name of Child:

Participant's ratings

1. ______________ 7. ______________

2. ______________ 8. ______________

3. ______________ 9. ______________

4. ______________ 10. _____________

5. ______________ 11. _____________

6. ______________ 12. _____________

Instructions for Scoring

- Write the participant's rating from the section above in the appropriate section of the table below
- Add up the participant's rating for each subscale, then divide by 4 and write the value in the Final Score column

Subscale	Items				Score / 4	Final Score
Internal visual imagery	**Q.2**	**Q.5**	**Q.8**	**Q.11**		
External visual imagery	**Q.3**	**Q.6**	**Q.9**	**Q.12**		
Kinesthetic imagery	**Q.1**	**Q.4**	**Q.7**	**Q.10**		