Motor imagery in children

The development of mentally respresenting movements

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Introduction

Imagine that you are going to touch your nose with your finger, but be sure not to move your body. You can almost feel your arm moving upwards, your hand reaching towards your face and finally feeling your fingertip on your nose. You have just been involved in a process called motor imagery. A formal definition of motor imagery is 'the internal simulation of a movement, without any overt motor output' (Decety & Grezes, 1999; Jeannerod, 1994; Sharma, Pomeroy, & Baron, 2006). Motor imagery relates to the activation of motor representations and shares cognitive processes with the planning and execution of movements (Decety & Grezes, 1999; Jeannerod, 1995). Several empirical lines of research provide evidence for the relation between motor imagery and execution of a movement. First, neuro-imaging studies in adults indicated that similar brain areas are active during execution and imagery of the same movement, such as the primary motor cortex, parietal regions and the cerebellum (for a review, see Case, Pineda, & Ramachandran, 2015). Second, the link between executing and imagining a movement is also evident from behavioural studies, showing that adult's imagery performance is constrained by similar task characteristics as actually performing that same movement (Decety, Jeannerod, & Prablanc, 1989; Parsons, 1994). Finally, motor imagery ability was found to be affected in children with developmental motor disorders such as cerebral palsy (CP; e.g., Crajé, van Elk, et al., 2010) and developmental coordination disorder (DCD; e.g., Wilson, Maruff, Ives, & Currie, 2001). Hence, diminished abilities to activate motor representations are at least associated with, but might even underlie motor control problems, which is in line with a tight coupling between motor imagery and motor execution.

The last decade, there is a growing body of interest in motor imagery ability of children. Most of these studies focus on the comparison of children with motor disorders and a typically developing control group, to examine whether motor imagery ability is affected in children with motor disorders (e.g., Lust, Geuze, Wijers, & Wilson, 2006; Williams, Omizzolo, Galea, & Vance, 2013). However, some studies specifically aimed at studying the development of movement representations via motor imagery in typically developing children, to obtain insight into motor control processes that can be related to children's motor development (e.g., Butson, Hyde, Steenbergen, & Williams, 2014; Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Smits-Engelsman & Wilson, 2012). This recent work shows that age does affect motor imagery ability, generally observing improved motor imagery ability across age (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Smits-Engelsman & Wilson, 2012). Up to date, it remains challenging to draw definite conclusions on the developmental trajectory of children's motor imagery, in particular its early emergence (for a review of previous insights into children's motor imagery ability, see Chapter 2). This thesis examines the development and emergence of motor imagery by conducting a series of cross-sectional and longitudinal experimental studies using different motor imagery paradigms (Chapters 3 to 7). Insight into the development and emergence of motor representations can enhance our understanding of motor processes during childhood. Moreover, motor imagery training has proven effective for rehabilitation in adults, for instance after stroke (Carrasco & Cantalapiedra, 2013). Therefore, insight into the age at which children start to accurately employ motor imagery and further developmental changes therein facilitate our understanding of whether motor imagery training is a feasible tool in pediatric rehabilitation.

Motor imagery ability in children

This thesis focuses on obtaining insight into the emergence and development of motor imagery ability. An overview of current insights into children's motor imagery and the outline of the thesis are described below. Chapter 2 provides details on the two most commonly used experimental paradigms to assess motor imagery and discusses current insights into motor imagery ability in typically developing children. Behavioural motor imagery paradigms are grounded in the notion that motor imagery and motor execution share cognitive motor processes. Hence, the employment of motor imagery is indicated when the imagined task performance adheres to the same task and motor constraints as the actual execution of the very same motor task.

Hand laterality judgment task

A classical paradigm to study mental rotation was designed by Shepard and Metzler (1971). Two identical or mirror images of geometrical objects were shown and participants were instructed to judge whether the objects were the same or not. Parsons (1987) adjusted the mental rotation paradigm, in order to examine whether motor processes are involved in mental representations. In the hand laterality judgment task (HLJ task), participants judge whether a picture of a hand stimulus is either a left hand or a right hand, by pressing a button at the corresponding side (Parsons, 1987). The hand stimuli are presented in different angles of rotation (varying between the fingers pointing up and down), and in different directions (varying from the fingers pointing towards the midline of the body [medial rotation] and away from the midline of the body [lateral rotation]). Furthermore, the presentation of the hands is either in back view or in palm view (see Figure 1.1 for two examples of hand stimuli). The two outcome measures are response accuracy (percentage of correct judgments) and response duration (duration from stimulus presentation to button press). Motor imagery ability is indicated when the pattern of accuracy and/or duration reflects biomechanical constraints of actual hand movements. More specifically, critical evidence for the employment of motor imagery is that participants take longer and/or are less accurate for judging hand stimuli that are rotated laterally (biomechanically more awkward) compared to medially rotated stimuli (biomechanically less awkward).

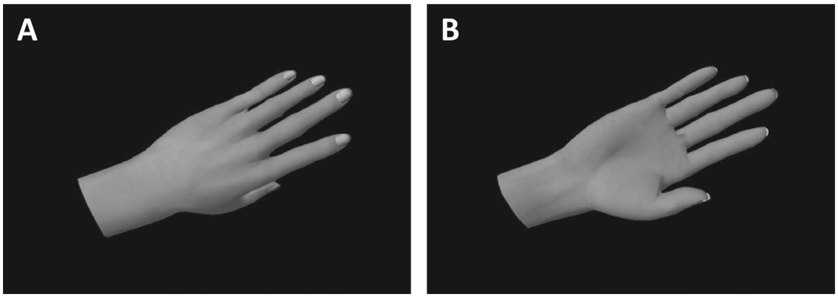

Figure 1.1. Two examples of hand stimuli for the hand laterality judgment task. A) Medial rotation of a left hand stimulus in back view; B) Lateral rotation of a right hand stimulus in palm view.

Previous HLJ task studies were predominantly aimed at comparing imagery ability between children with motor disorders and typically developing children (e.g., Williams, Thomas, Maruff, & Wilson, 2008; Wilson et al., 2004). Differences in HLJ task performance between children with atypical and typical development were generally taken as a direct reflection of differences in motor imagery ability. However, as the HLJ task can alternatively be performed by using non-motor imagery strategies (e.g., applying abstract rules), these differences in HLJ task performance might not be attributed to the use of motor imagery. In this thesis, it was therefore specifically determined whether children employed a motor imagery strategy to judge hand laterality, or whether alternative non-motor imagery strategies were employed. We introduced an innovative method that discriminates between different strategies to perform the HLJ task by means of three a-priori defined sinusoid models. These models describe the patterns of response duration and response accuracy as a function of rotation angle, each reflecting a different strategy. It was determined whether typically developing children employed a motor imagery strategy and whether the strategies that children employed differed across age (Chapter 3).

A consistent finding in typically developing children between 5 and 12 years of age was longer response durations and/or lower accuracy for hand stimuli that were rotated in the lateral direction, compared to the medial direction (e.g., Butson et al., 2014; Funk, Brugger, & Wilkening, 2005; Krüger & Krist, 2009; Toussaint, Tahej, Thibaut, Possamai, & Badets, 2013). Noteworthy, children who did not perform the HLJ task above chance were generally excluded from further analyses (this constitutes approximately 40% of 5- to 7-year-olds; Funk et al., 2005; Krüger & Krist, 2009). These observations thus indicate that imagery for judging hands is grounded in motor processes in children who were accurate at the task. However, previous cross-sectional studies on children's motor imagery ability provided inconsistent observations about whether age differences in HLJ task performance reflect an increase or decrease of motor imagery involvement.

For instance, whereas several studies suggest an increase in motor involvement across age (Conson, Mazzarella, Donnarumma, & Trojano, 2012; Krüger & Krist, 2009; Toussaint et al., 2013), Funk et al. (2005) and Sekiyama, Kinoshita and Soshi (2014) suggested a decreasing motor imagery involvement across age. Furthermore, Butson et al. (2014) did observe age-related differences in the effect of biomechanical constraints on response duration, but these differences did not reflect a systematic increasing or decreasing motor imagery involvement across age. The present thesis was specifically aimed at clarifying the involvement of motor imagery to perform hand laterality judgments across age. To this aim, developmental changes in motor imagery employment were determined by means of a three-year longitudinal design. Importantly, previous studies did not specifically examine motor imagery ability for children who did not perform above chance and these children were commonly excluded from further analyses (e.g., Butson et al., 2014; Funk et al., 2005; Krüger & Krist, 2009; Spruijt, van der Kamp, & Steenbergen, 2015a). As a consequence, insights in the early development and emergence of motor imagery might be biased or overlooked. We extended previous studies by additionally considering whether children who did not perform above chance employed a motor imagery strategy. Examining developmental changes in imagery strategies is particularly of interest in children who undergo a transition from not performing the HLJ task above chance at young age, towards performing the task above chance. In these children, developmental changes in the employed strategies might underlie changes in task accuracy (Chapter 4).

Mental chronometry paradigm

In the mental chronometry paradigm it is examined whether the actual performance of a motor task corresponds with the imagined performance of the same motor task. The most commonly used motor task is consecutive pointing towards targets (see Sirigu et al., 1995). The targets vary in width and/or amplitude, thereby varying task difficulty. The outcome measures are the duration of the actual movements and the duration of the imagined movements. Temporal congruence between the actual and imagined performance is taken as evidence for motor imagery ability, but only if the effects of task difficulty (i.e., compliance with Fitts' law) are similar for the actual and imagined performance.

Previous mental chronometry studies generally compared motor imagery performance of children with motor disorders and a typically developing control group, to examine whether motor imagery ability is diminished in these children (Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Maruff, Wilson, Trebilcock, & Currie, 1999). Only few studies examined the effect of age and showed improved motor imagery capacity between 5 and 12 years of age (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012), as evidenced by increasing temporal congruence, as well as increasing effects of task difficulty on the imagined task. Importantly, previous studies generally included groups with relatively wide age ranges and these studies were not aimed at determining whether the performance of a single age group reflected the engagement in motor imagery, or could alternatively reflect employment of a non-motor imagery strategy. This thesis aimed to determine the emergence of motor imagery on a conventional motor imagery pointing task by assessing whether task performance of single age groups showed indications of motor imagery use (temporal congruence and compliance with Fitts' law). Furthermore, it is considered whether motor imagery ability varied as a function of age by comparing groups including children of only one age (i.e., 6 vs. 7 vs. 8 years of age; Chapter 5).

It has been previously suggested that motor imagery performance might be dependent on the motor task that is used to assess motor imagery ability (Caeyenberghs, Tsoupas, et al., 2009; Crognier, Skoura, Vinter, & Papaxanthis, 2013; Fusco et al., 2014; Kunz, Creem-Regehr, & Thompson, 2009), for instance due to the experience with the movement. The generality of previous observations on the conventional pointing task was therefore also examined by determining age-related differences in children's motor imagery ability via mental chronometry of walking (Chapter 6).

Motor imagery as a rehabilitation tool

Motor imagery training has shown beneficial effects in a rehabilitation setting for promoting motor performance in adults, for instance after stroke (for reviews see Malouin & Richards, 2010; Zimmermann-Schlatter, Schuster, Puhan, Siekierka, & Steurer, 2008). The effect of mentally rehearsing movements on actual motor performance can be ascribed to stimulation of neural networks that are involved in controlling movements (e.g., Case et al., 2015). It has been suggested that children with developmental motor disorders, such as CP, might also benefit from motor imagery training (Steenbergen, Crajé, Nilsen, & Gordon, 2009). Thus far, only few studies have addressed motor imagery training in children (Asa, Melo, & Piemonte, 2014; Doussoulin & Rehbein, 2011; Taktek, Zinsser, & St-John, 2008; Wilson, Thomas, & Maruff, 2002). Motor imagery training can only be effectively applied in pediatric rehabilitation when children are able to engage in motor imagery (Steenbergen, Jongbloed-Pereboom, Spruijt, & Gordon, 2013). The lack of research on motor imagery training in children might therefore be explained by challenges that remain to determine the emergence and development of motor imagery ability in children. The present thesis aspires to aid in judging the feasibility of motor imagery training in children by gaining insight into children's ability to engage in motor imagery, which is a prerequisite for motor imagery training to be effectively applied in children. In a rehabilitation context, motor imagery training is mainly aimed at improving motor performance in individuals with motor disorders. Therefore, in addition to studying motor imagery ability in typically developing children, the concluding chapter examines the capability of individuals with CP to engage in motor imagery for an everyday motor task (Chapter 7).

Outline

To summarize, the thesis aimed at examining children's motor imagery ability, in particular its development and emergence. To this aim, we reviewed the literature on previous motor imagery studies in typically developing children (**Chapter 2**) and we performed several experimental studies using two behavioural motor imagery paradigms; hand laterality judgments and mental chronometry. We performed two studies employing the HLJ task to measure motor imagery ability. In **Chapter 3**, we examined whether the (motor) imagery strategies that children employ to judge hand laterality differ across age in children between 5 and 8 years of age. In addition to this cross-sectional HLJ task study, in **Chapter 4** we additionally present longitudinal results to reflect the developmental changes in motor imagery between 5 and 7 years of age.

For the remaining empirical chapters, we applied the mental chronometry paradigm to examine children's motor imagery ability. **Chapter 5** was aimed at determining whether 6- to 8-year-old children were engaged in motor imagery on a conventional goal-directed pointing task. Furthermore, this chapter presents age-related differences in motor imagery performance. Following suggestions that motor imagery performance might depend on the motor task (Bohan, Pharmer, & Stokes, 1999; Ferguson, Wilson, & Smits-Engelsman, 2015; Fusco et al., 2014), in **Chapter 6** we consider the generality of previous pointing observations by examining emergence and age-related differences in motor imagery for walking in children between 6 and 9 years of age. In the context of implementing motor imagery training for rehabilitation purposes, motor imagery training will target individuals with motor disorders. In contrast to the previously described studies that all examined typically developing children, the last empirical chapter addresses the ability of individuals with CP to engage in motor imagery, examined with mental chronometry of walking (**Chapter 7**).

The final chapter (**Chapter 8**) is dedicated to a discussion of our observations on the use of motor imagery on the experimental tasks, to draw general conclusions on the emergence of motor imagery ability and further developmental changes thereafter. Finally, the implications of our novel insights into children's motor imagery ability for application of motor imagery training in pediatric rehabilitation are discussed.


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Current insights in the development of children's motor imagery ability

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Abstract

Over the last two decades, the number of studies on motor imagery in children has witnessed a large expansion. Most studies used the hand laterality judgment paradigm or the mental chronometry paradigm to examine motor imagery ability. The main objective of the current review is to collate these studies to provide a more comprehensive insight in children's motor imagery development and its age of onset. Motor imagery is a form of motor cognition and aligns with forward (or predictive) models of motor control. Studying age-related differences in motor imagery ability in children therefore provides insight in underlying processes of motor development during childhood. Another motivation for studying age-related differences in motor imagery is that in order to effectively apply motor imagery training in children (with motor impairments), it is pertinent to first establish the age at which children are actually able to perform motor imagery. Overall, performance in the imagery tasks develops between 5 and 12 years of age. The age of motor imagery onset, however, remains equivocal, as some studies indicate that children of 5 to 7 years old can already enlist motor imagery in an implicit motor imagery task, whereas other studies using explicit instructions revealed that children do not use motor imagery before the age of 10. From the findings of the current study, we can conclude that motor imagery training is potentially a feasible method for pediatric rehabilitation in children from 5 years on. We suggest that younger children are most likely to benefit from motor imagery training that is presented in an implicit way. Action observation training might be a beneficial adjunct to implicit motor imagery training. From 10 years of age, more explicit forms of motor imagery training can be effectively used.

In a series of studies that have appeared in the last decade (Cho, Kim, & Lee, 2012; Lee, Song, Lee, Cho, & Lee, 2011; Page, Dunning, Hermann, Leonard, & Levine, 2011; Tamir, Dickstein, & Huberman, 2007), it was shown that motor imagery training can be beneficial for motor rehabilitation in adult patients with acquired brain damage, in particular stroke (for reviews see Dickstein & Deutsch, 2007; Malouin & Richards, 2010; Sharma et al., 2006; Zimmermann-Schlatter et al., 2008). Motor imagery is supposed to stimulate the neural networks that underlie the planning and control of movements. As such, motor imagery training in rehabilitation is regarded as a 'backdoor' to facilitate a patient's motor performance (Sharma et al., 2006).

Despite its proven effectiveness for rehabilitation in adult stroke patients, and despite converging evidence showing that problems in motor imagery are concomitant with motor control problems in congenital motor disorders such as cerebral palsy (CP) and developmental coordination disorder (DCD) (Crajé, van Elk, et al., 2010; Wilson et al., 2001), empirical studies on motor imagery training in these children are scarce (but see Wilson et al., 2002). A likely reason for this lack of research may be that the successful application of motor imagery training necessitates that the individual has a skilled capacity to perform motor imagery. While adults were repeatedly shown to be able to use motor imagery (e.g., Cerritelli, Maruff, Wilson, & Currie, 2000; Choudhury, Charman, Bird, & Blakemore, 2007a; Petit, Pegna, Mayer, & Hauert, 2003; ter Horst, Jongsma, Janssen, Van Lier, & Steenbergen, 2012), children's ability for motor imagery is not very clear. The present study reviews the empirical literature on motor imagery in children to delineate the capacity of children up to 12 years of age to engage in motor imagery. The studies that were selected after a search in the literature are analyzed to provide answers to two research questions. How does motor imagery develop during childhood? At what age are children able to reliably use motor imagery? These insights are necessary to judge the feasibility of motor imagery training to promote motor performance in young children with congenital motor disorders (Steenbergen et al., 2009; Steenbergen et al., 2013).

Motor imagery and its relation to motor performance

Probably the most influential conceptualization of motor imagery stems from Jeannerod (1994). He contended that motor imagery relates to the motor representation that is involved in the planning and execution of movements. In this view, the motor representation is a typically non-conscious process that generates or causes movements. Yet, the non-conscious motor representation can, under certain conditions, also be made conscious. Jeannerod (1994) refers to such a conscious motor representation as a motor image. "According to this definition, motor images are endowed with the same properties as those of the (corresponding) motor representation, that is, they have the same functional relationship to the imagined or represented movement and the same causal role in the generation of this movement" (Jeannerod, 1995, p.1419). Consequently, motor imagery and motor planning must be considered as functionally equivalent (Jeannerod, 1994). Motor imagery thus functions to internally simulate a future motor action without any overt motor output, i.e., the actual movement execution is inhibited (Decety & Grezes, 1999; Guillot, Di Rienzo, Macintyre, Moran, & Collet, 2012). An important, but not yet fully resolved issue in this respect is the content of the motor images (and the corresponding motor representations). Most accounts conceive of a motor image as an internal model of the goal of the action that can be represented at different levels (e.g., Wolpert, 1997). These forward (or predictive) internal models contribute to volitional control by anticipating and cancelling out the sensory consequences of a given movement (Vogt, Rienzo, Collet, Collins, & Guillot, 2013).

The link between motor imagery and motor performance is empirically supported by adult research. Neuro-imaging studies have repeatedly shown overlapping neural activity during the actual production of a movement and motor imagery of the same movement (Hanakawa, Dimyan, & Hallett, 2008; Lacourse, Orr, Cramer, & Cohen, 2005). This includes activity in the supplementary motor areas, cerebellum, premotor cortices and the parietal cortex. For example, the parietal cortex is thought to have a role in spatiotemporal aspects of motor planning, due to its processing of perceptual information and it involves the formation of an internal model of the goal of the action (Stephan et al., 1995). In addition, patients with lesions in the parietal cortex show impaired imagery of motor tasks, as expressed by a decreased capacity to estimate the duration of the task through motor imagery (Sirigu et al., 1996, see also "Mental chronometry paradigm").

Paradigms to study motor imagery

The vast majority of motor imagery research uses the hand laterality paradigm and/or the mental chronometry paradigm to examine motor imagery ability in children. In the hand laterality paradigm, participants typically judge whether a displayed hand stimulus is a left or a right hand. In the mental chronometry paradigm, participants both actually perform and imagine a specific movement task. In motor imagery, a movement is imagined from a first person perspective - as if actually producing the movement oneself. Consequently, motor imagery performance is affected by the same constraints as performing an actual movement. However, participants can use alternative strategies to perform the experimental tasks within the two paradigms, for instance applying abstract rules, motor memory, or imagining the movement from a third person perspective - as if watching someone else perform the movement. These latter strategies are not constrained by, or grounded in the motor system, and hence, it will be labeled as non-motor imagery. Importantly, however, the current review focuses exclusively on the use of *motor* imagery. Hence, it is pertinent that the empirical studies allow us to demarcate the use of motor imagery and non-motor imagery strategies. The notion that only motor imagery bears a direct relation to motor planning and control processes (see also Currie & Ravenscroft, 1997) can be used to make such a distinction at a behavioural level. As we will describe below, this is indeed the case for both the hand laterality and mental chronometry paradigms.

Hand laterality judgment paradigm

The first experimental paradigm that is frequently used to infer motor imagery ability is a forced-choice response task that involves hand laterality judgments. This task is a variation of classic mental rotation tasks. However, instead of judging objects, participants judge the laterality of bodily stimuli (see Figure 2.1), allowing determination of the use of motor imagery. For example, participants have to decide as quickly as possible whether the shown hand stimuli depict a left or a right hand. They do so by pressing a button that corresponds to the left or right hand, in general with their own hand palms facing down (de Lange, Helmich, & Toni, 2006; Parsons, 1994; Shenton, Schwoebel, & Coslett, 2004; ter Horst, van Lier, & Steenbergen, 2010). The hand stimuli are displayed in different angles of rotation (i.e., showing rotations varying between 0o with fingers pointing up to 180o with fingers pointing down) and in different directions (i.e., showing medial rotations with the fingers pointing towards the midline of the body, or lateral rotations with the fingers pointing away from the midline, see Figure 2.1). On occasions, the hands are displayed in different orientations as well (i.e., showing the back or palm of the hand, Figure 2.1).

Two outcome measures are generally analyzed: response accuracy and response duration. Response accuracy (i.e., the proportion of correct responses) is used to determine whether participants are able to solve the hand laterality judgment task above chance. Regardless of variations in response accuracy due to different rotation angles and orientations of the hand stimuli, in adults, the overall response accuracy is usually high with the proportion of correct responses rarely dropping below 90%. This indicates that adults can identify right and left hands accurately (Ionta & Blanke, 2009; Parsons, 1994; Shenton et al., 2004; ter Horst, van Lier, & Steenbergen, 2011). Response accuracy thus provides a first indication of the ability to solve the task.

The second outcome measure is response duration, that is, the time between presentation of the hand stimulus and the button press. Commonly, only the durations of the correct responses are included for further analyses. Similar to observations of mental rotation of non-body objects (Shepard & Metzler, 1971), in adults durations vary as a function of the rotation angle of the hand stimuli. Typically, the larger the deviation from the canonical orientation (i.e., the fingers pointing up), the more time it takes to mentally rotate the hand in order to identify it as a left or right hand, at least for back view hands (de Lange et al., 2006; Parsons, 1994; Shenton et al., 2004; ter Horst et al., 2010).

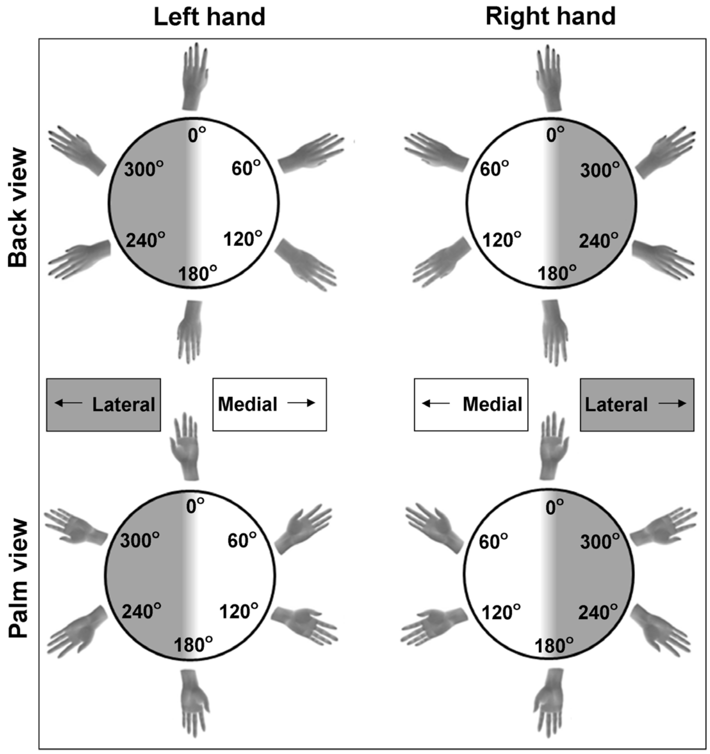

Figure 2.1. Examples of possible stimuli for the hand laterality judgment paradigm. Stimuli include left and right hands, commonly rotated over multiple angles of rotation and viewed from the back or the palm of the hand. Hands can be rotated to the medial side (rotation angles between 0° and 180°) and to the lateral side (rotation angles between 180° and 360°).

This pattern of response duration is taken as an indication that participants use mental rotation to solve the task. However, even though response accuracy and the effect of rotation angle on response duration are indicative for the process of mental rotation, it is critical to note that these are not sufficient to conclude that participants in fact use *motor* imagery. That is, participants can also use alternative non-motor strategies, for instance, they may apply an abstract rule or heuristic to judge hand laterality, or the rotation of the hand is imagined from a third person perspective. In sum, the use of *motor* imagery for hand laterality judgments is indicated if the pattern of response durations reflects the biomechanical constraints to which actual motor performance complies. For instance, rotating one's own hand in a lateral rotation (away from the midline of the body) is biomechanically more difficult than rotating it to the medial side (towards the midline of the body, see Figure 2.1). Hence, increased response durations (and sometimes decreased response accuracy) when mentally rotating lateral compared to medial hand stimuli reflect the use of motor imagery. In contrast, response durations are not affected by a lateral or medial rotation direction when non-motor imagery strategies are employed. Indeed, studies in adults generally showed that lateral hand stimuli are judged slower compared to medial hand stimuli (Parsons, 1994; Shenton et al., 2004; ter Horst et al., 2011). However, the degree to which this effect is found depends on the orientation of the stimulus. This is illustrated by a larger difference in response durations between medial and lateral stimuli for palm compared to back view hands in adults (Parsons, 1994; ter Horst et al., 2010). In a similar vein, incongruence between the participant's own hand orientation (i.e., with the back or palm side of the hand in view) and the orientation of the depicted hand results in increased response durations (and/or decreased response accuracy). The effect of own hand orientation on the response pattern was taken as evidence for motor imagery in adults (de Lange et al., 2006; Shenton et al., 2004). These behavioural indications of motor imagery in adults were confirmed at the neurophysiological level. In contrast to the employment of non-motor imagery strategies for mental rotation, brain activity during motor imagery shows substantial overlap with brain activation during actual motor performance (Dechent, Merboldt, & Frahm, 2004; Neuper, Scherer, Reiner, & Pfurtscheller, 2005; ter Horst, van Lier, & Steenbergen, 2013).

In the hand laterality paradigm, motor imagery development is reflected by age-related increases in the degree to which the imagery performance is affected by motor constraints. We therefore considered whether previous studies found an increasing (or perhaps decreasing) effect of the medial/lateral differences on the pattern of response duration with age. To determine age of onset of motor imagery use, we evaluated the studies with respect to the age at which children's mental rotation first display effects of motor constraints (faster responses for medial rotations and/or an effect of hand incongruence). However, before doing so, we first elaborate on the second paradigm for motor imagery, mental chronometry.

Mental chronometry paradigm

The second frequently used paradigm for assessing motor imagery is mental chronometry. Here, participants are instructed to actually perform a movement task and, in a separate block or session, to imagine themselves performing the very same movement task. Mental chronometry examines whether the durations of actually performing a task and imagining the same task correspond. A high congruence between actual and imagined durations is taken as evidence for the use of motor imagery. For example, in adult participants, high correlations between the duration of actual and imagined movements were reported for goal-directed finger pointing movements (Choudhury, Charman, Bird, & Blakemore, 2007b; Sirigu et al., 1996) and for goal-directed walking (Decety et al., 1989).

Importantly however, temporal congruence may imply motor imagery; yet, non-motor imagery strategies (such as motor memory, third person perspective imagery or counting; Munzert, Lorey, & Zentgraf, 2009; Sharma et al., 2006) cannot be automatically ruled out to account for the findings. To determine whether participants indeed employ motor imagery or instead a non-motor imagery strategy, it must also be ensured that the imagined performance is subject to the same motor constraints as the actual performance. An often-used experimental manipulation to ascertain this stems from the Fitts' law paradigm (Fitts, 1954). Participants perform goal-directed pointing movements either repeatedly towards one target (Visually Guided Pointing Task; VGPT), or consecutively towards several targets presented in a radial configuration (Virtual Radial Fitts' Task; VRFT). The width of the target and the distance towards the target is varied across trials (for an example of a radial Fitts' task, see Figure 2.2). Fitts (1954) described a lawful linear relation between the movement duration of pointing movements and the difficulty of the task (index of difficulty), represented by the ratio between the width of the target and the distance towards the target. Actual pointing movements adhere to this lawful relation (for a review, see Plamondon & Alimi, 1997). If participants use motor imagery in the mental chronometry paradigm, then imagined pointing should also be subject to Fitts' law. Therefore, a linear increase in imagined duration as a function of an increasing task difficulty is an indication of the use of motor imagery. For instance, Choudhury et al. (2007a) and Cerritelli et al. (2000) have shown that Fitts' law indeed applies for adult participants imagining visually guided pointing movements towards targets of varying width. In a similar vein, also for walking movements on paths of different length and width, adults showed compliance with Fitts' law when mentally performing the task (Bakker, de Lange, Stevens, Toni, & Bloem, 2007).

In the mental chronometry paradigm, motor imagery development would be associated with an increasing congruence between the imagined and the actual task performance with age. Hence, we examined whether previous studies found evidence to support an age-related increase in temporal congruence and an increasing effect of task manipulations on the imagined task. Accordingly, the age of onset of motor imagery use would be reflected by the youngest age at which there is unambiguous evidence that children's actual and imagined movement durations correlate and at the same time are similarly affected by task manipulations.

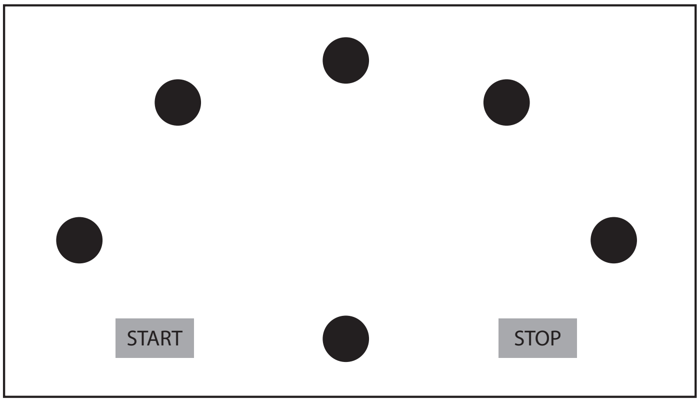

Figure 2.2. Schematic presentation of the radial Fitts' task. The participants start in the green 'start' box, and then move to the central circle. From the central circle, they move back and forth to the five radial targets and end the movement in the 'stop' box. Mental chronometry studies using the Fitts' task commonly vary target width across trials.

Review of the literature on motor imagery in typically developing children

In order to establish at what age children use motor imagery, we performed a literature search on February 2nd 2015, with a combination of the search terms 'motor imagery' and 'children'. This resulted in 54 hits in Pubmed, and 97 hits in the Web of Science search engine. Including or replacing for the search terms 'development', 'mental rotation' and 'mental chronometry' did not result in additional relevant studies, except for one article that was found when searching with the search terms "mental rotation" and "children" in Web of Science. From these studies we selected English written experimental studies that met the following two criteria: 1: the study involved a behavioural task to study motor imagery; 2: the study involved typically developing children between 5 and 12 years of age. Studies that focused on brain activation without a behavioural motor imagery task and studies that only investigated atypically developing children were excluded. The vast majority of research on motor imagery has employed the hand laterality and/or mental chronometry paradigm and they are therefore the focus of the present study. Consequently, one study that used a double-task paradigm to study motor imagery ability was excluded from further discussion (Piedimonte, Garbarini, Rabuffetti, Pia, & Berti, 2014). Furthermore, studies that used a reachability paradigm to determine motor imagery ability are not used in the remainder (e.g., Gabbard, Cordova, & Ammar, 2007). The rationale for excluding these studies is that it cannot be ascertained from this paradigm if the experimental tasks actually test motor imagery. Alternatively, the children may adopt an alternative non-motor imagery strategy and, for instance, merely report the perceived affordances. Review articles were also excluded. Three studies reviewed literature on motor imagery in children with motor disorders (Adams, Lust, Wilson, & Steenbergen, 2014; Gabbard & Bobbio, 2011; Steenbergen et al., 2009) and one study reviewed literature on action representation in typically and atypically developing children (Gabbard, 2009). The literature search, however, did not return any review studies that specifically focused on the *development* of motor imagery in *typically developing* children.

The search yielded a total of 30 empirical studies that were selected for consideration (Table 2.1 and Table 2.2). Fourteen studies focused exclusively on typically developing children, whereas the primary focus of the remaining sixteen was on children with motor disabilities, such as CP and DCD. Yet, for the present purpose it is of interest that these studies also included age-matched groups of typically developing children for comparison. These latter groups are taken into consideration. We will discuss these studies with respect to the observed age-related differences in and onset of motor imagery ability.

The hand laterality judgment paradigm in children

Table 2.1 presents sixteen studies that employed the hand laterality judgment paradigm. It is evident that nearly all studies examined the relation between response duration and angle of rotation of the depicted hands for the total group of children. A consistent finding was an effect of rotation angle on response duration, indicating increased durations as the rotation angle of the depicted hands increased. Several studies reported this relationship for children between 5 and 12 years of age (Caeyenberghs, Tsoupas, et al., 2009; Funk et al., 2005; Krüger & Krist, 2009; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams et al., 2008; Wilson et al., 2004). The overall observed response accuracy was found to exceed 70% in studies with children older than 7 years of age. In 5- to 7-year-olds, over half (i.e., 60%) of the children performed above chance when judging back and palm view hands (Funk et al., 2005; Krüger & Krist, 2009). These collective results suggest that the majority of children between 5 and 12 years of age are capable of mentally rotating hands, as was previously shown for non-body part objects (e.g., Frick, Ferrara, & Newcombe, 2013; Marmor, 1975).

In addition to reporting an effect of rotation angle, several studies also assessed the impact of biomechanical constraints on total group response duration and/or accuracy via a comparison of responses to laterally and medially rotated hands. All studies that did examine the medial-lateral difference (Funk et al., 2005; Krüger & Krist, 2009; Lust et al., 2006; Noten, Wilson, Ruddock, & Steenbergen, 2014; Toussaint et al., 2013; Williams, Anderson, et al., 2011; Williams et al., 2013; Williams, Reid, Reddihough, & Anderson, 2011) found increased response durations for hands in lateral rotations relative to medial rotations, even when only back view stimuli were included in the study (Lust et al., 2006; Toussaint et al., 2013; Williams, Anderson, et al., 2011; Williams et al., 2013;

Williams, Reid, et al., 2011). This indicates that imagery in children from 5 to 12 years of age is grounded in motor processes. An exemplary study with respect to determining the effects of biomechanical constraints was performed by Deconinck et al. (2009). They demonstrated that among 9-year-olds, biomechanical constraints affected laterality judgments in two ways. First, the judgments for laterally rotated back and palm view hands resulted in longer response durations (and were slightly, but significantly less accurate) compared to hands in medial rotations, while mental rotation of letters was not affected by medial or lateral rotations. Second, it was also found that hand orientation of the participant (i.e., with the palm up or down) relative to the orientation of the depicted hand influenced response durations (but not accuracy). Thus, response durations increased when the orientation of the participant's and depicted hand were incongruent compared to when hand orientations were congruent. Similar results were reported for 5- to 7-year-old children that accurately performed the task (Funk et al., 2005). Taken together, the studies indicate that 5- to 12-year-old children employed the motor imagery strategy to judge hand laterality.

Besides examining overall motor imagery ability for groups of children within a certain age range, several studies have also addressed age-related differences in motor imagery in children. For instance, Caeyenberghs, Tsoupas et al. (2009) compared back view hand laterality judgment performance of 7- and 8-year-olds, 9- and 10-year-olds, and 11- and 12-year-olds. They found that overall the younger children responded slower and less accurate than older children, but no interaction between rotation angle and age was found. This suggests that children used the same strategy across age. Funk et al. (2005) compared the performance of 5- to 7-year-old children with the performance of adults (back and palm view stimuli). They concluded that the impact of biomechanical constraints and hand posture on laterality judgments was enhanced in the children relative to adults. They report that "these results […] strongly suggest that young children's kinetic imagery is guided by motor processes, *even more so than in adults*" (Funk et al., 2005, pp. 407 - 408). Toussaint et al. (2013) and Krüger and Krist (2009) challenged this claim as biomechanical constraints had stronger effect in 8-year-olds than in 6-year-olds (back view; Toussaint et al., 2013) and when comparing 7-year-olds and adults to 5-year-olds (palm view; Krüger & Krist, 2009). In the latter study, it was concluded that "there was no indication of a particular strong link between sensorimotor and imagery processes in kindergartners [i.e., 5-year-olds]; rather, the contrary appeared true." (Krüger & Krist, 2009). Similarly, Conson et al. (2013) also indicated that motor involvement was more pronounced in older participants, when comparing 11- and 12-year-olds to 14- and 15-year-olds and 17- and 18-year-olds. Surprisingly, they did not find a significant effect of biomechanical constraints on laterality judgments for back and palm view stimuli in 11- and 12-year-olds. Finally, Butson et al. (2014) also determined whether hand laterality judgment performance varied across age in 5- to

Table 2.1

Overview of studies that used the hand laterality judgment paradigm

Author	**Age (years)**	**Stimuli**	**Motor imagery instructions?**	**Considered variables** [#]
Dey et al. (2012)	5 – 17	Back view	No	A
Wilson et al. (2004)*	8 – 12	Back and palm view	No	D
Williams et al. (2006)*	7 – 11	Back view	Yes	D
Williams et al. (2008)*	7 – 11	Back view	Yes	D
Caeyenberghs, Tsoupas, et al. (2009)	7 – 12	Back view	Yes	D, A
Deconinck et al. (2009)*	9	Back and palm view	No	D, B
Lust et al. (2006)*	9 – 12	Back view	No	D, B
Williams, Anderson, et al. (2011)*	8 – 12	Back view	Yes	D, B
Williams, Reid, et al. (2011)*	8 – 12	Back view	No	D, B
Williams et al. (2013)*	7 – 11	Back view	No	D, B
Noten et al. (2014)*	7 – 12	Back and palm view	Yes	C, D, B
Funk et al. (2005)	5 – 7	Back and palm view	No	C, D, B
Krüger and Krist (2009)	5 – 7	Exp1: Back Exp2: Palm	No	C, D, B, A
Toussaint et al. (2013)	6 & 8	Back view	No	D, B, A
Conson et al. (2013)	11 – 18	Back and palm view	No	D, B, A
Butson et al. (2014)	5 – 12	Back and palm view	Yes	C, D, B, A

[#] The variables that were considered in the studies are indicated by: C = response accuracy above chance, D = rotation angle, B = biomechanical constraints, A = age

* The study's primary focus is on motor imagery in motor disabled children. Here we only present the results for the typically developing control group.

Table 2.1 (continued)

Overview of studies that used the hand laterality judgment paradigm

Author	**Main results**
Dey et al.	No effect of age on response duration Effect of age on response accuracy
Wilson et al.	Effect of rotation angle on response duration No effect of rotation angle on response accuracy
Williams et al.	Effect of rotation angle on response duration and response accuracy
Williams et al.	Effect of rotation angle on response duration and response accuracy
Caeyenberghs, Tsoupas, et al.	Effect of rotation angle and age on response duration and response accuracy
Deconinck et al.	Effect of rotation angle and biomechanical characteristics on response duration and response accuracy
Lust et al.	Effect of rotation angle and biomechanical characteristics on response duration
Williams, Anderson, et al.	Effect of rotation angle and biomechanical characteristics on response duration
Williams, Reid et al.	Effect of rotation angle and biomechanical characteristics on response duration and response accuracy
Williams et al.	Effect of rotation angle and biomechanical characteristics on response duration
Noten et al.	21% of participants not above chance level Effect of rotation angle and biomechanical characteristics on response duration
Funk et al.	40% participants not above chance level Effect of rotation angle and biomechanical characteristics on response duration
Krüger and Krist	Exp 1: effect of rotation angle on response duration Exp 2: 40% of 5-year-olds not above chance level; 17% of 7-year-olds not above chance level Effect of rotation angle, biomechanical characteristics and age on response duration Effect of rotation angle and age on response accuracy
Toussaint et al.	Effect of rotation angle, biomechanical characteristics and age on response duration and response accuracy
Conson et al.	Effect of rotation angle, biomechanical characteristics and age on response duration
Butson et al.	20% of participants not above 50% response accuracy Effect of rotation angle, biomechanical characteristics and age on response accuracy and response duration

11-year-olds. Most 5- and 6-year-old children were not yet able to perform the task accurately above 50% chance level for back view stimuli. Response accuracy increased with age in 7- to 11-year-olds. Biomechanical constraints were only found to affect response durations for back and palm view stimuli in the 8-, 9- and 11-year-olds, but not in the 7- and 10-year-olds.

Taken together, the studies on age-related differences in motor imagery indicate that children's ability to accurately perform the task (response accuracy) increases with age. However, there are some inconsistencies concerning the ability of 5- to 7-year-old children to accurately perform hand laterality judgments. Butson et al. (2014) reported that most children of 5 and 6 years old were not able to accurately perform the task, while Krüger and Krist (2009) and Funk et al. (2005, pp. 407 - 408) showed that only 40% of the 5- to 7-year-olds performed below chance. Most studies reported age differences on motor involvement, indicating that the use of motor imagery develops across age. Importantly, the reported age-related differences in the use of motor imagery vary across studies. Funk et al. (2005) suggested that motor involvement decreases with age. This suggests that children are more involved in the motor imagery strategy, while other strategies to solve the task (i.e., non-motor imagery) are increasingly enlisted in the task at a later age. If true, then this may accord well with one of the main tenets of Piagetian theory that the development of cognitive abilities is constructed from sensorimotor processes. That is, Piaget (1954) described that after cognitive processes emerge from the motor system, the role of motor processes in cognitive development decreases. In contrast, other studies showed an increase in motor involvement for older participants (Conson et al., 2013; Krüger & Krist, 2009; Toussaint et al., 2013). Moreover, the results of Butson et al. (2014) are inconclusive about whether the age effects reflect an increase or decrease of motor involvement with age, as the 7- and 10-year-olds showed no motor involvement, while 8-, 9- and 11-year-olds did. Therefore, currently no definite conclusions can be drawn from studies using the hand laterality judgment paradigm about the exact development and age of onset of motor imagery between 5 and 12 years of age.

The mental chronometry paradigm in children

The literature search yielded fifteen studies that used the mental chronometry paradigm in children (Table 2.2). Iosa et al. (2014) studied actual and imagined goal-directed walking in a small group of 4- to 14-year-olds (n=8). They did not find a significant correlation between the actual and imagined durations. Molina et al. (2008) had 5- to 7-year-old children walk and imagine walking towards a target. The correlation between movement duration of the two tasks was significant for the 7-year-olds but not for their younger peers. In the study by Skoura et al. (2009), a maze drawing task was performed by children aged 6 to 10. Children of 6 and 8 years did not differ with respect to temporal congruence between actual performance and imagined performance, but the 10-year-olds showed significantly higher temporal congruence than the 8-year-olds. Hoyek et al. (2009) employed an obstacle course task to study mental chronometry. Temporal congruence in the 11- and 12-year-olds was significantly higher than in 7- and 8-year-old children. Finally, Gabbard et al. (2011) used a sequential finger movement task in 7-, 9-, and 11-year-old children. Both actual and imagined movement duration increased for longer sequences. In contrast to age-related differences in the other studies, Gabbard et al. (2011) reported significant correlations between movement and imagined durations only for the two *younger* groups. Collectively, these studies indicate that temporal congruence between actual and imagined performance increases from 5 to 12 years.

Still, the finding of temporal congruence in itself cannot unambiguously indicate that motor imagery is used, because participants may also have used alternative non-motor imagery strategies or even counting to solve the task. To confirm that the task was actually solved using motor imagery, ten out of fifteen studies additionally tested whether task manipulations affected the actual task and the imagined task in a similar fashion. They did so by using a paradigm based on Fitts' law (see Table 2.2). Lewis et al. (2008) and Williams et al. (2012) used the Visually Guided Pointing Task (VGPT) in which the 8- to 12-year-old children made repeated pointing movements to a target. Task difficulty was systematically manipulated by varying target width. They found that for the group as a whole, durations of the actual as well as the imagined movements adhered to Fitts' law. Four studies that included children between 5 and 16 years of age reported both temporal congruence between the two tasks and compliance with Fitts' law for both tasks on a group level (Caeyenberghs, van Roon, Swinnen, & Smits-Engelsman, 2009; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001). Together, these studies showed that 5- to 12-year-olds as a group use motor imagery in a mental chronometry paradigm. However, they do not allow us to draw conclusions about onset or development, because they did not directly compare children of different ages.

Other studies extended the work on motor imagery by focusing on the age-related differences in motor imagery. First, Caeyenberghs, Wilson et al. (2009) reported that in groups of children between 6 and 16 years old, temporal congruence significantly increases with age. With respect to Fitts' law, it was found that for the actual movement task, there was good linear fit between duration and index of difficulty for all age groups. Still, the linear fit in the imagery task increased with age; the 6- to 7-year-olds showed weaker fit than the 10- to 16-year-olds. Second, Caeyenberghs, Tsoupas et al. (2009) reported similar significant age-related increases in temporal congruence for 7- to 8-, and 9- to 12-year-old children. In addition, the linear fit between movement duration and index of difficulty for both tasks combined was weaker for the 7- and 8-year-olds than for the 9- and 10-, and 11- and 12-year-old children. Third, Smits-Engelsman and Wilson

Table 2.2

Overview of studies that used the mental chronometry paradigm

Author	**Age (years)**	**Task**	**Considered variables** [#]
Iosa et al. (2014)*	4 – 14	Goal-directed walking	T
Molina et al. (2008)	5 & 7	Goal-directed walking	T, A
Skoura et al. (2009)	6 – 10	Drawing a maze	T, A
Hoyek et al. (2009)	7 – 12	Obstacle course	T, A
Gabbard et al. (2011)	7 – 11	Sequential finger movements	T, A
Crognier et al. (2013)	9 – 21	VGPT	T, B, A
Maruff et al. (1999)*	9 – 11	VGPT	T, B
Wilson et al. (2001)*	8 – 11	VGPT	T, B
Lewis et al. (2008)*	8 – 12	VGPT	B
Caeyenberghs, Wilson, et al. (2009)	6 – 16	VRFT	T, B, A
Caeyenberghs, Tsoupas, et al. (2009)	7 – 12	VRFT	T, B, A
Caeyenberghs, van Roon, et al. (2009)*	5 – 16	VRFT	T, B
Williams et al. (2012)*	8 – 12	VGPT	B
Williams et al. (2013)*	7 – 11	VGPT	T, B
Smits-Engelsman and Wilson (2012)	5 – 29	VRFT	T, B, A

Note: VRFT = Virtual Radial Fitts Task: 5 radial targets; VGPT = Visually Guided Pointing Task: repeated movements to 1 target; Condition = imagery vs. actual movement

[#] The variables that were considered in the studies are indicated by: T = temporal congruence, B = task constraints, A = age

* The study's primary focus is on motor imagery in motor disabled children. Here we only present the results for the typically developing control group.

Table 2.2 (continued)

Overview of studies that used the mental chronometry paradigm

Author	**Main results**
Iosa et al.	Effect of condition on movement duration
	No correlation movement durations
Molina et al.	Correlation movement durations: effect of age
Skoura et al.	Effect of age and condition on movement duration
	Correlation movement durations: effect of age
Hoyek et al.	Effect of age and condition on movement duration
	Correlation movement durations: effect of age
Gabbard et al.	Effect of age and condition on movement duration
	Correlation movement durations for the 7- and 9-year-olds
Crognier et al.	Effect of age and condition on movement duration
	Movement durations affected by task constraints: effect of age and condition
Maruff et al.	Movement durations according to Fitts' law, effect of condition
	Correlation movement durations
Wilson et al.	Movement durations according to Fitts' law, no effect of condition
	Correlation movement durations
Lewis et al.	Movement durations according to Fitts' law, effect of condition
Caeyenberghs,	Movement durations according to Fitts' law: effect of age and condition
Wilson, et al.	Correlation movement durations: effect of age
Caeyenberghs,	Movement durations according to Fitts' law, effect of age and condition
Tsoupas, et al.	Correlation movement durations: effect of age
Caeyenberghs,	Movement durations according to Fitts' law, effect of condition
van Roon, et al.	Correlation movement durations
Williams et al.	Movement durations according to Fitts' law
Williams et al.	Movement durations according to Fitts' law, effect of condition
	Correlation movement durations
Smits-Engelsman	Movement durations: effect of age, Index of Difficulty and condition.
and Wilson	Correlation movement durations: effect of age

(2012) examined performance in the mental chronometry paradigm in participants from 5 to 29 years. It was evident that temporal congruence for the younger participants (5 to 7 and 8 to 10 years) was significantly lower than for the older participants. Although index of difficulty affected actual movement durations in all age groups, a comparable effect was absent for the imagined movement durations in children below 10 years of age. This suggests that the younger children did not use motor imagery to perform the imagery task. This result is in line with a fourth study that addressed age differences (Crognier et al., 2013). Crognier et al. tested whether manipulating task constraints for a pointing task (high vs. low inertia) would similarly affect the motor and imagined task. In contrast to performance in the motor task, the imagined task was not affected by task constraints in 9- and 11-year-olds, indicating that they did not employ motor imagery to perform the task, whereas 14- and 21-year-olds were found to employ motor imagery.

In sum, the findings from the mental chronometry paradigm indicate that children's ability to enlist motor imagery develops until at least 12 years of age as attested by age-related increases in temporal congruence and compliance with Fitts' law for the imagined task. The results of these studies however beg the question as to whether motor imagery occurs in children younger than 10-11 years of age, or whether younger children use alternative non-motor strategies to solve the task.

The development of motor imagery in children

In the past two decades numerous studies have been performed on motor imagery in typically developing children. Most studies examined overall motor imagery ability in groups of children within a certain, often relatively large, age range. Nonetheless, some studies also have directly compared motor imagery ability between groups of children of different age. The current study is the first to provide an overview of studies on motor imagery ability in typically developing children, with a special focus on age-related differences and delineating the age at which children can reliably invoke motor imagery. Obtaining more insight in the age-related ability of children to enlist motor imagery is important for implementing motor imagery training in pediatric rehabilitation.

The current review focused on determining how motor imagery ability develops with age. Studies using the mental chronometry paradigm reported that the contribution of motor imagery becomes more salient between 5 and 12 years of age (i.e., the imagery condition more strongly complies with Fitts' law) (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012). There is considerable consensus from studies employing the hand laterality paradigm that from 5 to 12 years of age, children become more accurate and faster in solving the task (Butson et al., 2014; Caeyenberghs, Tsoupas, et al., 2009; Krüger & Krist, 2009). Importantly, however, it does not necessarily follow from the enhanced ability to successfully perform the task that with development children do actually use motor imagery more or become more proficient in using motor imagery. Alternative strategies, such as for instance non-motor imagery (i.e., with a third rather than first person perspective) may also increasingly contribute to solving the mental imagery tasks successfully. In line with studies using the mental chronometry paradigm, most studies using the hand laterality paradigm also reported that motor involvement increased with age (Conson et al., 2013; Krüger & Krist, 2009; Toussaint et al., 2013), albeit at younger ages than in mental chronometry studies. Nonetheless, Funk et al. (2005) contradict the evidence for an increasing role of motor imagery with age, by showing that for 5- to 7-year-old children who accurately performed the task, hand laterality judgments are fully grounded in motor processes, while later in development the contribution of motor processes decreases (Funk et al., 2005). It is difficult to explain the deviating results of Funk et al. (2005) based on differences in the experimental set-up. Although studies show methodological differences, for instance with regard to inclusion of back and/or palm view hand stimuli and specific first person perspective motor imagery instructions (Table 2.1), these differences do not seem to provide a systematic explanation for the discrepant findings. For instance, even though the stimulus set of Funk et al. and Conson et al. (2013) both included back and palm view stimuli and no specific motor imagery instructions were provided, Funk et al. report a decrease of biomechanical constraints in imagery performance with age, whereas Conson et al. showed the opposite effect, that is, an increased effect of biomechanical constraints (see also Krüger & Krist, 2009; Toussaint et al., 2013).Taken together, most studies indicate that motor imagery increases with age, but it is difficult to draw definite conclusions on the exact developmental trajectory. In this respect, future work on motor imagery development would surely benefit from a longitudinal design, which remarkably, has never been adopted thus far.

With respect to the age at which children start to use motor imagery, studies employing the hand laterality judgment paradigm reported that little over half of 5- to 7-year-old children are already capable of using motor imagery to accurately perform the task including palm view stimuli (Funk et al., 2005; Krüger & Krist, 2009). Butson et al. (2014), however, could not confirm these observations, and reported that only a few of the 5- to 6-year-olds were able to accurately perform the task. The latter finding is surprising, as Butson et al. used hand stimuli that were relatively easy to judge (back view, with the fingers pointing up) to determine whether children were able to judge hand laterality. Moreover, they reported that 7-year-olds did not appear to enlist motor imagery reliably. In fact, Conson et al. (2013) argued that even children as old as 11 or 12 years did not use a motor imagery strategy – considering other reports for the hand laterality paradigm, this study is clearly an exception. Conson et al. included palm view stimuli, that were previously reported to induce the effect of biomechanical constraints on adult’s task performance, compared to back view performance (see Parsons, 1994;

ter Horst et al., 2010). The orientation of the stimuli can therefore not account for the absence of motor imagery indications. Furthermore, a lack of specific task instructions could not explain the absence of motor imagery reported by Conson et al., as also Funk et al. and Krüger and Krist did not provide specific task instructions. Taken together, these studies suggest that differences in methodological set-up between studies cannot easily account for the differences in task performances between the studies. However, a late emergence of motor imagery is in line with observations in the mental chronometry paradigm (Smits-Engelsman & Wilson, 2012), which indicate that the use of motor imagery does not emerge before 10-12 years of age. Only very few children of 5 to 7 years of age have been shown to be capable of using motor imagery on the mental chronometry paradigm (Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012).

In sum, previous motor imagery studies suggest that possibly a small proportion of the 5-year-olds is able to accurately use motor imagery. Yet the evidence is equivocal, and hence the exact age of onset of motor imagery use for both paradigms remains to be verified. Clearly, there are significant individual and task differences in young children's motor imagery. These inter-individual differences in motor imagery ability might be explained by cognitive and motor abilities that can facilitate or constrain motor imagery development, such as executive functioning (e.g., working memory, inhibition, attention) (see also Krüger & Krist, 2009), motor planning ability, movement experience (see also Caeyenberghs, Tsoupas, et al., 2009) and IQ. For example, working memory has been suggested to be related to motor imagery ability in adults (Choudhury et al., 2007a; Gabbard, Lee, & Cacola, 2013; Malouin, Belleville, Richards, Desrosiers, & Doyon, 2004). The rapid development of executive functions during childhood (e.g., Brocki & Bohlin, 2004) might therefore be tightly coupled to motor imagery development. Challenges for future studies remain to determine factors such as working memory that might impact children's motor imagery development. In doing so, we recommend to first establish whether individual participants use motor imagery and then compare the children that do successfully use motor imagery to the children that are not using motor imagery.

The hand laterality judgment paradigm and the mental chronometry paradigm are commonly used measures of motor imagery in adults (as described in the review of Munzert et al., 2009). From the overview of the literature on age-related differences in children's motor imagery ability it is evident however, that the results commonly differ between these two imagery tasks. Most hand laterality judgment studies suggest that a considerable number of 5- to 8-year-olds and nearly all older children are able to use motor imagery (Caeyenberghs, Tsoupas, et al., 2009; Funk et al., 2005; Krüger & Krist, 2009; Toussaint et al., 2013). By contrast, for the mental chronometry paradigm it is estimated that only one out of ten 5- to 7-year-old children use motor imagery, while only after 10 years of age all children do so (Smits-Engelsman & Wilson, 2012). Obviously, the discrepant developmental patterns may arise from distinct task characteristics that hamper the expression of motor imagery ability more during mental chronometry than during judgment of hand laterality. A likely explanation may be sought in the nature of the paradigms, invoking motor imagery either explicitly or implicitly. In the mental chronometry paradigm children are often made aware and instructed to use motor imagery explicitly, whereas the hand laterality judgment paradigm is more implicit and instructions regarding motor imagery are often lacking (cf. Caeyenberghs, Tsoupas, et al., 2009). Previous studies showed that implicit learning (i.e., without instructions that make children aware of what they have to learn or do) is relatively unaffected by age, whereas explicit learning shows clear increases with age (Meulemans, Van der Linden, & Perruchet, 1998; Vinter & Detable, 2008). Accordingly, in young children motor imagery may be more easily induced without instructions that make children aware of what they have to do, while explicit instructions to employ motor imagery may actually hinder its use, especially at a younger age. In line with this suggestion, the present results show that young children already used motor imagery in a task with implicit instructions (hand laterality judgment paradigm), but did not use motor imagery in a task with explicit instructions at young age (mental chronometry paradigm).

In addition to an extensive body of literature supporting the beneficial effects of incorporating motor imagery training in standard rehabilitation protocols in adults (e.g., Malouin & Richards, 2010), two studies in children in the age range of 7 to 12 years old underline the potential of motor imagery training in children (Doussoulin & Rehbein, 2011; Wilson et al., 2002). However, prior to a systematic and effective application of motor imagery training in pediatric rehabilitation, knowing from what age and under what pre-conditions children are able to enlist motor imagery is of utmost importance. In this respect, the current review suggests that children as young as 5 years can enlist motor imagery in an implicit way, while explicitly adopting motor imagery might not be possible before 10 years of age. Obviously, if confirmed, then this is particularly relevant for developing age-related content of motor imagery training programs. With respect to implicit motor imagery training for the youngest children, an interesting adjunct may be offered by action observation training. Motor imagery and action observation substantially overlap in terms of their neuro-anatomical basis (Filimon, Nelson, Hagler, & Serenoa, 2007; Grezes & Decety, 2001). This commonality may provide a promising avenue for stimulating the networks involved in motor control and development (Buccino, Solodkin, & Small, 2006). For example, a recent study on action observation in addition to actually performing movements showed clear benefits of action observation for motor performance in 6- to 11-year-old children with cerebral palsy (Buccino et al., 2012). Contrary to children who watched videos without motor content, children who were watching videos of others producing actions led to an increase in motor function.

Accordingly, action observation may be a valuable aid to motor imagery in the very young children that cannot be instructed about using motor imagery. For children older than 10 years, more explicit forms of motor imagery training seem viable. Future research must examine whether these instructions can be as detailed as has been successfully used in motor imagery training in adults with stroke (e.g., Dijkerman, Ietswaart, Johnston, & MacWalter, 2004). Subsequently, identifying factors that limit or facilitate the use of motor imagery can aid the selection of children that may benefit from implicit or explicit motor imagery training.


3

Predictive models to determine imagery strategies employed by children to judge hand laterality

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Abstract

A commonly used paradigm to study motor imagery is the hand laterality judgment task. The present study aimed to determine which strategies young children employ to successfully perform this task. Children of 5 to 8 years old (N = 92) judged laterality of back and palm view hand pictures in different rotation angles. Response accuracy and response duration were registered. Response durations of the trials with a correct judgment were fitted to a-priori defined predictive sinusoid models, representing different strategies to successfully perform the hand laterality judgment task. The first model predicted systematic changes in response duration as a function of rotation angle of the displayed hand. The second model predicted that response durations are affected by biomechanical constraints of hand rotation. If observed data could be best described by the first model, this would argue for a mental imagery strategy that does not involve motor processes to solve the task. The second model reflects a motor imagery strategy to solve the task. In line with previous research, we showed an age-related increase in response accuracy and decrease in response duration in children. Observed data for both back and palm view showed that motor imagery strategies were used to perform hand laterality judgments, but that not all the children use these strategies (appropriately) at all times. A direct comparison of response duration patterns across age sheds new light on age-related differences in the strategies employed to solve the task. Importantly, the employment of the motor imagery strategy for successful task performance did not change with age.

A classic paradigm to study mental imagery of body parts is the hand laterality judgment (HLJ) task (Parsons, 1987), in which participants make forced-choice judgments of whether pictures of hands display a right or a left hand. Participants can employ different mental imagery strategies to successfully solve the HLJ task. First, participants can imagine mentally rotating *their own hand* into the same position as the displayed hand, but without actually producing that movement. This strategy involves a first person or egocentric perspective, and is typically referred to as motor imagery (Conson et al., 2012; Sirigu & Duhamel, 2001; Steenbergen, van Nimwegen, & Crajé, 2007). Motor imagery is a cognitive process that involves the internal simulation of a movement without actually performing it (Decety & Grezes, 1999; Jeannerod, 1994; Sharma et al., 2006). The imagined hand rotation is presumed to exploit a motor representation for hand movements, and is therefore subject to the same constraints as actual hand movements (Lust et al., 2006). Second, the HJL task can also be performed using strategies other than motor imagery. In particular, participants can mentally rotate the hand from a third person or allocentric perspective. Rather than exploiting a motor representation of hand movements, this strategy treats the hand like any other detached object. Put differently, within this strategy mental rotation is not constrained by or grounded in the motor system. This strategy is often referred to as visual imagery (Brady, Maguinness, & Ni Choisdealbha, 2011; Conson et al., 2012; Lust et al., 2006; Steenbergen et al., 2007; Wilson et al., 2004). In the current study we are mainly interested in discriminating between mental imagery that is constrained by the motor system, and mental imagery that is not. We will therefore use the labels motor imagery and non-motor imagery.

Previous studies that examined the HLJ task in 5- to 12-year-old children have generally shown that HLJ task performance is affected by motor constraints, thus implying motor imagery is used to successfully solve the task (e.g., Funk et al., 2005; Williams, Reid, et al., 2011). However, most of these studies were not specifically aimed at determining whether HLJ task performance can also be understood using alternative non-motor imagery strategies, and the age-related differences therein. The purpose of the present study is therefore to determine whether children of 5 to 8 years old indeed engage in motor imagery or whether they adopt non-motor imagery to perform the HLJ task. In doing so, we also aimed to address age-related differences in the imagery strategies that children employ. To accomplish these aims, we used an innovative method to discriminate between motor and non-motor imagery strategies. We developed a-priori sinusoid models that reflect the different strategies and examined how well they could predict actual HLJ task performance.

In the HLJ task, left and right hand pictures are displayed in different angles of rotation (i.e., showing hand rotations varying between 0° with finger pointing up to 180° with fingers pointing down), in different directions (i.e., showing medial rotations with the fingers pointing towards the midline of the body or lateral rotations with the fingers pointing away from the midline), showing either the palm or back of the hand. Figure 3.1 illustrates a standard set of stimuli presented in the HLJ task. Mental imagery performance is commonly evaluated using response accuracy and response duration as dependent variables (e.g., Caeyenberghs, Tsoupas, et al., 2009; Deconinck et al., 2009; Krüger & Krist, 2009).

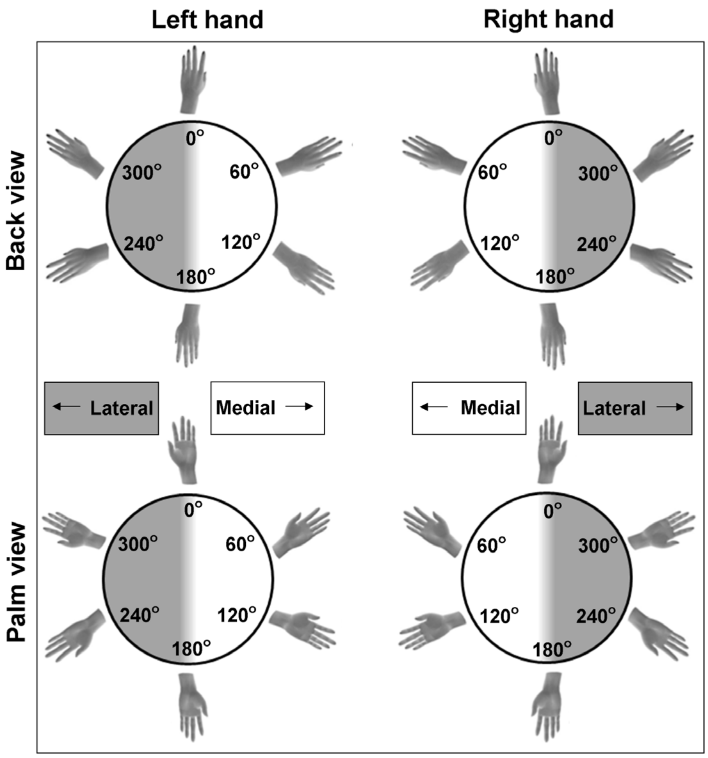


Figure 3.1. Stimulus set (right and left hands; back and palm view) for the different rotation angles (0°; 60°; 120°; 180°; 240°; 300°). Rotation angles between 0° and 180° represent medial rotations; rotation angles between 180° and 360° represent lateral rotations, irrespective of hand.

The response durations for mentally rotating an object are systematically affected by rotation angle, with larger angles relative to the neutral 0°–rotation resulting in longer response durations, up to a maximum for the 180°–rotation (Dalecki, Hoffmann, & Bock, 2012; Parsons, 1994; Petit et al., 2003; Shepard & Metzler, 1971). Although the *rotation angle* can affect response duration irrespective of whether a non-motor imagery or a motor imagery strategy is used, the *direction of rotation* is presumed to only affect response durations for motor imagery strategies. In the case of a non-motor imagery strategy, hands that are rotated medially or laterally result in the same response durations as long as the rotation angle is the same (Brady et al., 2011). In other words, a pattern of response durations that is symmetric around the 0°–rotation indicates a non-motor imagery strategy. By contrast, as motor imagery is subject to the same constraints as actual performance, the duration to mentally rotate one's own hand to a biomechanically 'awkward' lateral posture (i.e., rotating the hand away from the central body axis) results in prolonged durations compared to rotating one's hand towards a more 'comfortable' medial posture (i.e., rotating the hand towards the medial body axis) (de Lange et al., 2006; Parsons, 1994; Sekiyama, 1982; ter Horst et al., 2010; Tomasino & Rumiati, 2004). Thus, a pattern of response durations that is asymmetric around the 0°–rotation indicates a motor imagery strategy (Brady et al., 2011). Another indication for the involvement of motor imagery is the observation that the effects of rotation angle and direction of rotation on *actual* hand movement durations depend on the posture of the participants' hands (Parsons, 1994). Parsons (1994) showed that with the back of the hand facing upwards, physical hand rotation durations increase with rotation angle, with only small differences between lateral and medial rotations. In contrast, with the palm of the hand facing upwards, the differences between lateral and medial rotations are much more pronounced (Parsons, 1994). Accordingly, when rotation direction similarly affects the actual and imagined movement responses, the use of a motor imagery strategy is indicated. In sum, motor and non-motor imagery strategies in the HLJ task can be discriminated by considering the effects of rotation angle and direction of rotation on imagery response durations and by determining the differences in the response duration patterns for back and palm views.

Previous studies using the HLJ task in children have examined the effects of rotation angle and the direction of rotation on response durations. It was found that the laterality judgments for back and palm view hands by 5- to 12-year-old children are a function of rotation angle (Caeyenberghs, Tsoupas, et al., 2009; Williams et al., 2006; Williams et al., 2008; Wilson et al., 2004) and the direction of the rotation (Butson et al., 2014; Deconinck et al., 2009; Funk et al., 2005; Krüger & Krist, 2009; Lust et al., 2006; Williams, Anderson, et al., 2011; Williams et al., 2013; Williams, Reid, et al., 2011). This suggests that primary school children, taken as a group, indeed use motor imagery to solve the HLJ task. Three studies directly considered age-related differences in children's HLJ task performance. Krüger and Krist (2009) reported that in contrast to 7-year-olds, the effect of motor constraints was "not so distinct" (p. 256) in 5-year-olds, as only the response durations for right hand pictures were affected by the direction of rotation. Similarly, Toussaint, Tahej, Thibaut, Possamai and Badets (2013) recently indicated that the difference in response durations between lateral and medial rotations was larger in 8-year-olds than in 6-year-olds. Although these observations suggest that the contribution of motor imagery in judging hand laterality progresses between 5 and 8 years of age, they do not address the age at which children start to rely on motor imagery relative to non-motor imagery strategies. Butson, Hyde, Steenbergen and Williams (Butson et al., 2014) suggested that biomechanical constraints affect response durations in children of 8, 9 and 11 years old that were able to perform the task correctly, but not in children of 7 and 10 years old. Based on additional results that biomechanical constraints were reflected in response accuracy, they concluded that most 7- to 11- year olds were engaged in motor imagery to perform the HLJ task, but left for future research to designate younger children's use of motor imagery strategies.

The present study uses a-priori defined predictive sinusoid models that predict the changes in response duration patterns as a function of either the rotation angle (H1) or as a function of the rotation angle and direction of rotation (H2). These two models thus predict response duration patterns that would arise from employing either a non-motor or a motor imagery strategy to solve the HLJ task. These models were validated in a pilot experiment with adults, which confirmed that they can indeed discriminate between the two imagery strategies (see Appendix 3.1). Examining the fit between the model predictions and actual response duration patterns for 5- to 8-year-old children allows us to determine the imagery strategy that children use to perform the HLJ task, and consequently, the age-related differences therein.

The sinusoid models

Because hand pictures were rotated in a flat surface in a 360° full circular fashion, sinusoid models were used to predict response duration patterns as a function of rotation angle. The first model predicts that neither changes in rotation angle, nor changes in direction of rotation systematically influence the response duration patterns. This H0 model is described by a sinusoid with amplitude 0 (response duration = amplitude * sin (angle – phase shift) + intercept). This is graphically represented by a straight, horizontal line (Figure 3.2A). As the response durations do not vary as a function of rotation angle or the direction of rotation, the H0 model represents a performance strategy other than mental imagery, such as the application of an abstract rule or identification on the basis of idiosyncratic visual cues (as suggested by ter Horst et al., 2010).

The second model predicts changes in the response duration pattern that are symmetric around the 0°–rotation. In this H1 model, response durations change only as a function of rotation angle. An increase in rotation angle from 0° up to 180° results in longer response durations, irrespective whether the rotation is medially or laterally (Figure 3.2B). This H1 model is described as a sinusoid with a phase shift of 90° (response duration = amplitude * sin (angle – phase shift) + intercept). The phase shift of 90° reflects that response durations are shortest (i.e., fastest responses) at a 0°–rotation and largest when the hand stimuli are rotated over 180° (Figure 3.2B). As the model

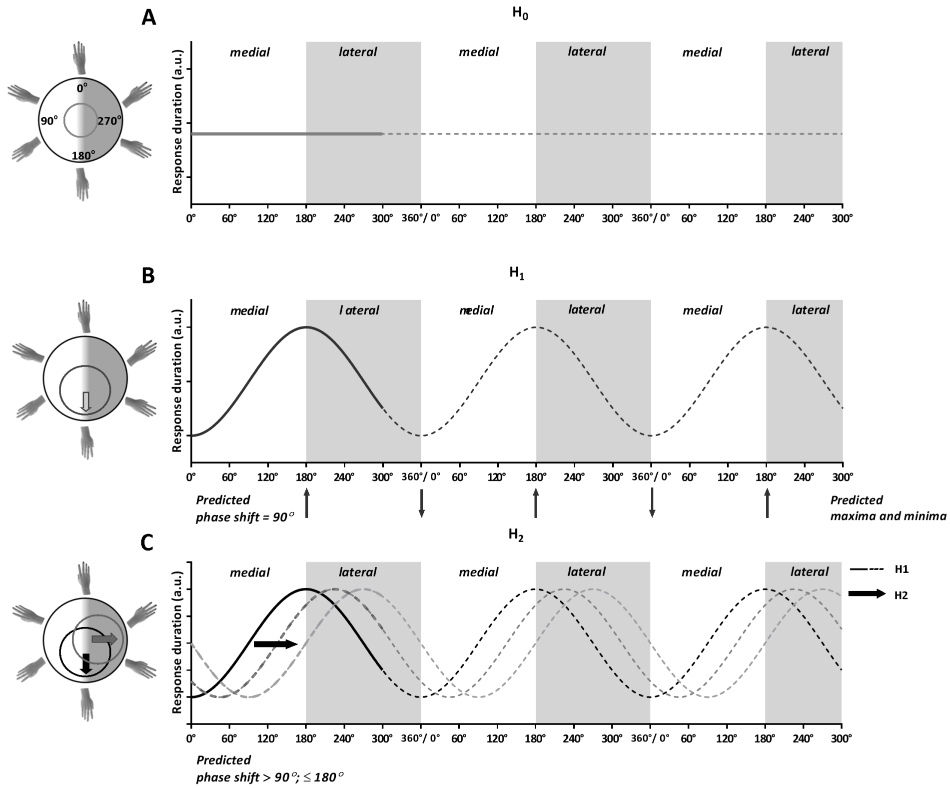


Figure 3.2. Modeled response duration patterns.

Left: Modeled distribution of response durations. The y-axis represents rotation angle, ranging from up (0°) to down (180°). The x-axis represents the direction of rotation, ranging from medial (white area) to lateral (grey area). The distance from the centre of the axes to the line represents the response durations.

Right: Modeled response duration curve over different angles of rotation. The solid lines represent the modeled curves (first wavelength). The dotted lines (second and third wavelength) were added to better visualize the modeled curves.

A) Depicts the H0: no effect of rotation angle or direction. Amplitude = 0.

B) Depicts the H1: with an increase in rotation angle, there is an increase in response duration. Phase shift = 90°.

C) Depicts the H2: The H1 curve (black line) is shifted to the right, representing an increase in response duration as a function of a rotation in the lateral direction (grey lines). Phase shift > 90°; ≤ 180°.

only includes an effect of rotation angle, and not the direction of rotation, the model represents a non-motor imagery strategy. The amplitude reflects the strength of the effect of rotation angle, i.e., the higher the amplitude, the stronger the effect of rotation angle on response duration patterns.

The third model predicts the asymmetric effect on imagery response durations around the 0°-rotation related to the direction of rotation. The H2 model predicts that lateral hand rotations result in longer response durations compared to medial rotations. The H2 model comprises a similar sinusoid, but with an additional phase shift that is larger than 90° and smaller or equal to 180° (response duration = amplitude * sin (angle – phase shift) + intercept). The response durations decrease for medially rotated hands and increase for laterally rotated hands (Figure 3.2C). The phase shift can vary from 90° (i.e., response durations are predominantly affected by rotation angle, cf. H1 model) up to 180° (i.e., response durations are predominantly affected by the direction of rotation). As the H2 model encompasses the direction of rotation, it represents a motor imagery strategy: mental rotation of the hand is subject to the same motor constraints as actual hand rotations (i.e., more awkward rotations take more time) (Parsons, 1994; ter Horst et al., 2010). Note that this model includes a scenario involving an effect of direction of rotation only (i.e., phase shift = 180°, thus without an additional effect of the rotation angle).

Current study

The current study examines the imagery strategies that children between 5 and 8 years of age use to solve the HLJ task. Prior work on the HLJ task in children mainly focused on general effects of the rotation angle and/or direction of rotation on imagery response durations. Only a few studies compared the effects between age groups, or determined the effects at one specific age. In the current study, we determine the combined effect of rotation angle and direction of rotation for the total group of children and for each individual child. Critically, we assess the phase shift parameter as this distinguishes the H1 model for non-motor imagery from the H2 model for motor imagery. Consequently, we can identify the involvement of motor imagery strategy to solve the HLJ task. Furthermore, regression analyses on the fitted parameters of the individual children allow establishing age-related differences in employed imagery strategies. We hypothesize that children's HLJ task performance will be affected by both the rotation angle and the direction of rotation, indicating that they adopt a motor imagery strategy (indicated by the H2 model with a phase shift larger than 90° and smaller or equal to 180°). In line with observations in adults (Parsons, 1994) we expect to find the direction of rotation effect to be more pronounced for judgments of palm view than for back view judgments (indicated by a larger phase shift). Finally, we expect more pronounced rotation direction effects with increasing age (indicated by larger phase shifts), as it was previously found that motor involvement increases between 5 and 8 years of age (Krüger & Krist, 2009; Toussaint et al., 2013).

Methods

Participants

A total of 92 right-handed, typically developing children between 5.2 and 8.9 years (M = 6.91; SD = 1.0) were recruited from mainstream primary schools in the Netherlands. Nonverbal intelligence quotient (IQ) was estimated using two subtests of the Dutch version of the Wechsler Nonverbal Scale of Ability, first edition (Wechsler & Naglieri, 2008). Up to 7 years of age, children performed the Matrices and Recognition subtests, while the 8-year-olds performed the Matrices and Spatial Recognition subtests. The reported reliability of these subtests is considered sufficient for estimating IQ (Matrices: α = 0.77; Recognition: α = 0.64; Spatial Recognition: α = 0.74) (Jonkman, Kooij, Wechsler, & Naglieri, 2008). The average IQ was 103 (SD=13.9) and 45.7% of the participants was male. The study has been approved by the local ethics committee of the Faculty of Social Sciences at the Radboud University Nijmegen (ECG2012-2402-018). Parents provided written informed consent prior to the experiment.

Material and procedure

A computerized HLJ task was used, in which children judged whether a picture displayed a left or a right hand. The children were comfortably seated at a table, facing a laptop. They placed the left hand on a button at the left hand side and the right hand on a button at the right hand side. The hands were covered with a black cloth in order to prevent the children from watching their hands. The procedure was as follows. First, a white fixation cross was presented in the middle of the black screen for a random duration between 1000 and 1500 milliseconds. Subsequently, a picture of a hand was presented in the middle of the screen. The children were instructed to indicate whether the displayed hand was a left hand or a right hand by pressing the corresponding button as fast as possible. After the response was given, the picture disappeared and the fixation cross was again shown until the next stimulus was presented. The children were instructed that they were not allowed to make any hand and/or head rotations during the judgment.

The stimuli were pictures of left and right hands, rotated in six different rotations: 0°; 60°; 120°; 180°; 240°; 300° (Figure 3.1). Stimuli with a rotation angle of 0° showed the hand with the fingers pointing upwards, stimuli with a rotation angle of 180° displayed the hand with the fingers pointing down. Rotation angles for left hand stimuli were defined in a clockwise manner, while rotation angles for right hand stimuli were defined in a counter-clockwise manner. Consequently, stimuli with rotation angles between 0° and 180° were medially rotated and stimuli with rotation angles between 180° and 360°

degrees were laterally rotated. Finally, the stimuli were presented in two different views. In the first block, the stimuli showed the back of the hands (Figure 3.1, top panels), while in the second block they showed the palm of the hand (Figure 3.1, bottom panels). Block order was the same for all children. Each unique stimulus was presented three times, resulting in 36 randomly ordered trials for each of two views. Six additional practice trials of different rotation angles were performed prior to the start of each block.

Data analysis

<u>Response accuracy</u>

We first established whether or not the children performed the HLJ task above chance level. Based on a binomial distribution (p = 0.50 for each trial), individual performance was significantly above chance level when more than 23 out of 36 stimuli were correctly identified. Individual chance scores were determined for each view (back and palm) separately. Subsequently, we used analysis of variances to compare age and IQ scores of the children that were able to successfully perform the HLJ task to the children that did not successfully perform the task.

<u>Response duration</u>

The response durations were only analyzed for the children who performed above chance. In addition, as we were primarily interested in the strategies used to successfully perform the task, trials with an incorrect judgment were removed (i.e., 12% of the trials). Finally, outlier trials, which were defined as response duration < 250 ms or response duration > mean response duration + 3*standard deviation, were also excluded from further analysis (i.e., 2% of the trials). Response durations were averaged across three repetitions of each of the 12 stimuli for the back and palm view separately, resulting in four datasets of response duration for the six rotation angles; a set for the back view of the left hand; for the back view of the right hand; for the palm view of the left hand; and a set for the palm view of the right hand (see Figure 3.1).

Goodness of fit F-tests were used to model the response duration distribution as a function of the rotation angle and the direction of rotation in GraphPad Prism 6. First, the children performing above chance were analyzed as one group. That is, group curves were fitted on the individual averaged response durations of the six rotation angles per data set (back and palm view, left and right stimuli). The procedure comprised of three steps: i) Fitted group parameters (intercept, amplitude and phase shift) were compared between the four different data sets. When the curves of different sets shared all parameters, then the data sets were pooled for further analyses. ii) Next, it was tested if a sinusoid curve with amplitude > 0 (H1, H2) described the observed data better than a sinusoid with amplitude = 0 (H0). iii) If H0 was rejected, it was tested whether the phase shift is different from 90° (H1) or whether the phase shift is different from a value between 90º and 180º (H2). A Bonferroni correction was used (back and palm view, three models) that resulted in an alpha level of $p = 0.0083$. This analysis procedure using sinusoid models to discriminate between motor and non-motor imagery strategies was validated in a pilot experiment with adults (see Appendix 3.1).

Moreover, for each individual child sinusoid curves were determined on the individual averaged response durations of the six rotation angles. This resulted in an intercept, amplitude and phase shift parameter for each child. By means of linear regression analyses we tested whether the individually fitted parameters could be predicted by age. These tests were performed for the back and palm view data separately.

Results

Response accuracy

Table 3.1 presents the response accuracy, age and IQ of the children performing at chance level and below chance level on the back and palm view. For both back and palm view it was found that the children who did correctly perform the task were older than the children who did not (Table 3.1; Back: $F(1,91) = 10.5$, $p = 0.002$, $\eta^2 = 0.10$; Palm: $F(1,91) = 15.3$, $p = 0.000$, $\eta^2 = 0.15$). Furthermore, IQ was significantly higher in the children who did perform the HLJ task above chance for palm view compared to the children who did not manage to solve the task systematically (Table 3.1; $F(1,90) = 7.91$, $p = 0.006$, $\eta^2 = 0.081$). These differences in IQ were not found for back view ($p = 0.24$).

Table 3.1

Response accuracy, age and IQ for the children that performed at chance and above chance

	Back view		**Palm view**	
	At chance	*Above chance*	*At chance*	*Above chance*
Percentage of total group	8.7%	91.3%	25%	75%
Number of errors (SD)	16.4 (0.89)	4.25 (0.37)	18.0 (0.56)	4.20 (0.33)
Age (SD)	5.88 (0.15)	7.01 (0.11)	6.26 (0.21)	7.13 (0.11)
IQ (SD)	97.6 (4.3)	104 (1.5)	96.4 (2.4)	105 (1.7)

Response duration

For the group that performed above chance, the fitted group parameters did not significantly differ for the back view stimuli of the left and right hand; hence the two data sets were pooled. This resulted in the following group model: response duration (back view) = 0.8801 * sin(angle – 110.4º) + 2.838 (Figure 3.3A). As shown in Table 3.2, the fitted phase shift parameter (110.4º) was significantly larger than 90º and significantly smaller than 180º (consistent with the H2 model). Hence, the resulting sinusoid shows that both the rotation angle and the direction of rotation affected the response durations when judging hands from the back.

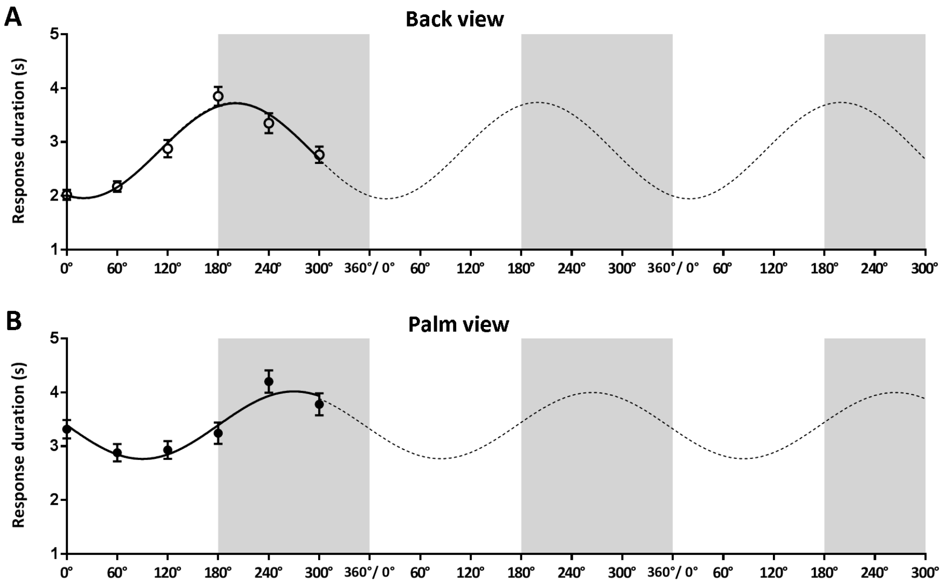


Figure 3.3. Response duration as a function of rotation angle. The solid lines represent the fitted sinusoid curves for the observed response durations (first wavelength). The dotted lines (second and third wavelengths) were added to better visualize the fitted curves. The data points in the first wavelength represent the mean response durations and standard error of means per rotation angle. Grey areas mark laterally rotated stimuli. *A*) Back view; *B*) Palm view.

Table 3.2

Fitted parameters total group

Fitted	**Tested**	**Back view results**			**Palm view results**		
parameter	**against**	$F(1,501)$	p	η^2	$F(1,411)$	p	η^2
Amplitude	≈ 0	104	0.000*	0.38	49.0	0.000*	0.26
Phase shift	= 90°	12.6	0.000*	0.071	48.6	0.000*	0.26
Phase shift	= 180°	91.1	0.000*	0.35	0.51	0.48	0.004

F-Tests of goodness of fit for the fitted parameters for back and palm view

** Significant (p < 0.0083; Bonferroni corrected)*

Also, for the palm view stimuli, the fitted group parameters did not significantly differ between left and right hand stimuli. The two data sets were therefore pooled. This resulted in the following model equation for the total group: response duration (palm view) = 0.6392 * sin(angle – 175.1°) + 3.390 (Figure 3.3B). The fitted phase shift parameter was significantly larger than 90°, but did not differ significantly from 180° (consistent with the H2 model). This indicates that the palm view judgments were only affected by direction of rotation, with minimum response durations at 90° (medial) and maximum response durations at 270° (lateral). The tests of fit parameters are listed in Table 3.2.

The individually fitted curves for the back and palm view are presented in Figure 3.4. Table 3.3 presents the average fitted parameters for the individual participants. For the back view, the individual fit of four participants (5.2; 5.2; 6.9; 7.7 years old) did not reach significance. The individual fits did not result in a significant sinusoid curve for these individuals, reflecting that they did not use an imagery strategy. Therefore, they were excluded from the regression analysis on the fitted parameters. Five participants showing a trend towards significance (amplitude > 0; $p < 0.1$) were included. Figure 3.5A shows that age both predicted the individually fitted intercept ($F(1,79) = 11.3$, $p = 0.001$, $R^2 = 0.13$) and amplitude ($F(1,79) = 5.7$, $p = 0.019$, $R^2 = 0.07$). However, the fitted phase shifts did not vary as a function of age ($p = 0.30$) (Figure 3.5A). For the palm view, the individual fit of seven participants (5.9; 5.9; 5.9; 7.1; 7.5; 7.6; 7.9 years old) did not reach significance and these individuals were excluded. Six participants showing a trend were included. It was found that age only predicted the fitted intercepts ($F(1,61) = 4.3$, $p = 0.043$, $R^2 = 0.07$), whereas the fitted amplitude ($p = 0.20$) and phase shift ($p = 0.78$) did not vary as a function of age (Figure 3.5B).

Accordingly, Figure 3.5 illustrates that older children made faster judgments. The finding that the effects of rotation angle and direction of rotation (phase shift) were similar across age indicates that age did not seem to affect the strategies to solve the HLJ task.

Table 3.3

Average fitted parameters individual participants

Back view results			**Palm view results**		
Intercept (in s) (SD)	*Amplitude (in s) (SD)*	*Phase shift (in degrees) (SD)*	*Intercept (in s) (SD)*	*Amplitude (in s) (SD)*	*Phase shift (in degrees) (SD)*
2.84 (1.19)	0.95 (0.58)	111 (24)	3.39 (1.03)	0.90 (0.62)	163 (54)

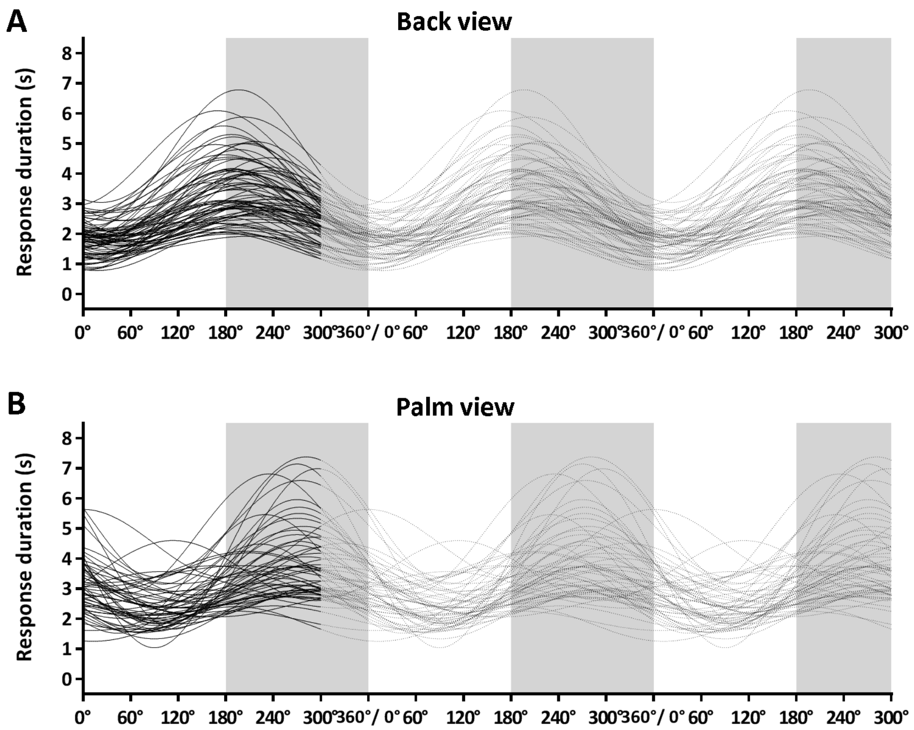


Figure 3.4. Response duration as a function of rotation angle. The black lines represent the fitted sinusoid curves for all individuals (first wavelength). The grey lines (second and third wavelength) were added to better visualize the fitted curves. Grey areas mark laterally rotated stimuli. *A*) Back view; *B*) Palm view.

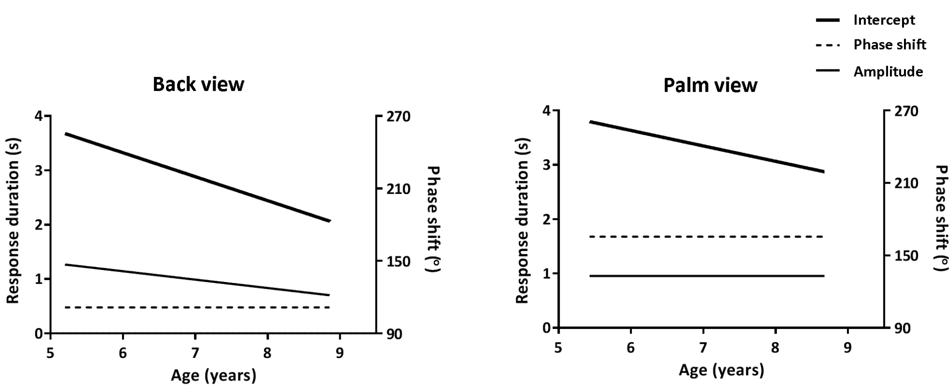


Figure 3.5. Linear regression on the fitted intercept (in seconds), amplitude (in seconds) and phase shift (in degrees) as a function of age (in years). *Left*: Back view; *Right*: Palm view.

Discussion

The present study examined the mental imagery strategies that children between 5 and 8 years of age use to successfully solve the HLJ task. The HLJ task is predominantly used to compare imagery ability between typically developing children and children with motor disorders (Deconinck et al., 2009; Lust et al., 2006; Williams, Anderson, et al., 2011; Williams et al., 2013; Williams, Reid, et al., 2011; Williams et al., 2006; Williams et al., 2008; Wilson et al., 2004). Generally, these studies have interpreted HLJ task performance as a direct expression of the adoption of motor imagery. Similarly, differences in HLJ task performance between typically developing children of different age have been attributed to increases in the use of motor imagery (Caeyenberghs, Tsoupas, et al., 2009; Krüger & Krist, 2009; Toussaint et al., 2013). However, motor imagery is not the only imagery strategy that can be adopted to perform the HLJ task (Steenbergen et al., 2007; Wilson et al., 2004). Hence, the present study attempts to account for the involvement of motor and non-motor imagery strategies in 5- to 8-year-old children who successfully solved the HLJ task. To this end, the response duration data were fitted to a-priori defined sinusoid models that describe response duration patterns for different imagery strategies, based on previous empirical findings. The models not only allow assessing the imagery strategy that is adopted by the children, but also potential age-related changes therein. In brief, the results demonstrated that for both back and palm view, children's mental rotation was affected by biomechanical constraints (i.e., the H2 model was not falsified). This indicates that they used motor imagery in case they had performed the HLJ task successfully. Importantly, although the ability to correctly perform the task increased with age, there were no age-related differences in the motor involvement (i.e., the fitted phase shift parameter did not vary as a function of age). This underscores that once children successfully solve the HLJ task, the motor imagery strategy they employ remains unaltered until 8 years of age. We discuss these findings in more detail below, starting with the age-related differences in response accuracy.

The observed age-related increase in the capability to correctly perform the HLJ task is in line with previous work (Caeyenberghs, Tsoupas, et al., 2009; Krüger & Krist, 2009; Toussaint et al., 2013). This indicates that from 5 to 8 years of age, older children become more proficient in correctly solving the HLJ task. Children that were able to do so on the palm view had higher IQ than children who were not. Hence, the development towards more proficient HLJ task performance may relate to a better understanding of task instructions, better working memory functioning, more abstract thinking and/or merely being able knowing left from right.

The improved capability in HLJ task performance with age, however, does not allow direct inferences regarding changes in the employed imagery strategy. Basically, the present findings indicate that children between 5 and 8 years old adopt motor imagery to successfully perform the task, irrespective of their age. First, the response duration patterns best fitted the H2 model, indicating that rotation angle and direction of rotation of the hands affected imagery performance durations in a similar way as durations of physical movement performance (Parsons, 1994). These effects of biomechanical constraints were found for both back and palm views, albeit that the direction of rotation had a stronger effect for palm view (as evidenced by the larger phase shift) (see Parsons, 1994). In fact, the palm view showed an effect of direction of rotation only (i.e., the phase shift parameter did not differ from 180°). In other words, for rotations up to a maximum at 180° palm view judgments response durations did not increase as a function of increasing rotation angle. Nonetheless, the rotation direction predominantly affected response durations, with prolonged durations for laterally rotated stimuli (270°), compared to medially rotated stimuli (90°). This indicates that mental rotation predominantly involved motor imagery, without non-motor imagery contributions. However, we have to be careful in concluding that palm view judgments rely more on motor imagery than back view judgments, because in the current design the back and palm view blocks were not counterbalanced. Hence, any difference can also be attributed to order or learning effects.

The observed individual phase shifts in the back and palm view did not change as a function of age, indicating that there were no age-related differences in the employed imagery strategy. Moreover, the observed individual amplitude of the palm view did also not change with age. This indicates that the effects of rotation angle and direction of rotation on response duration patterns did not change with age. We therefore conclude that between 5 and 8 years of age, children adopted a similar strategy when successfully judging hand laterality. Yet, there was a clear age effect for response speed. The older children responded faster, as indicated by the intercept parameter that significantly decreased with age. This difference does not reflect changes in employed strategies, but can alternatively be explained by changes in information processing speed across age. Our findings diverge somewhat from previous studies that suggested that motor involvement increased with age between 5 and 8 years of age (Krüger & Krist, 2009; Toussaint et al., 2013). Except for differences in stimulus sets (e.g., the inclusion of foot and/or non-body stimuli in previous work), a likely reason for this discrepancy is the methods used to pinpoint the adopted imagery strategy. Unlike previous approaches, in which effects of the rotation angle and direction of rotation of the hand stimuli were determined separately, the current approach takes the cumulative effects of these factors into account. This allows precise establishment of the imagery strategy adopted and the current evidence clearly indicates that the employed mental imagery is grounded in motor constraints, which remained the same across age. Importantly, a validation experiment in adults confirmed that the new approach can indeed distinguish between motor and non-motor imagery strategies (Appendix 3.1). A final reason for the discrepancy between previous and current findings may be the inclusion of children that performed the HLJ task at chance level (Toussaint et al., 2013). In fact, comparing the imagery strategies adopted by children who successfully identified the laterality of the hand stimuli with those of children who could not is an important issue for future work. Using the current a-priori defined modeling approach would allow assessing whether children that fail to correctly judge hand laterality employ different, less appropriate strategies (e.g., indicated by the phase shift parameter).

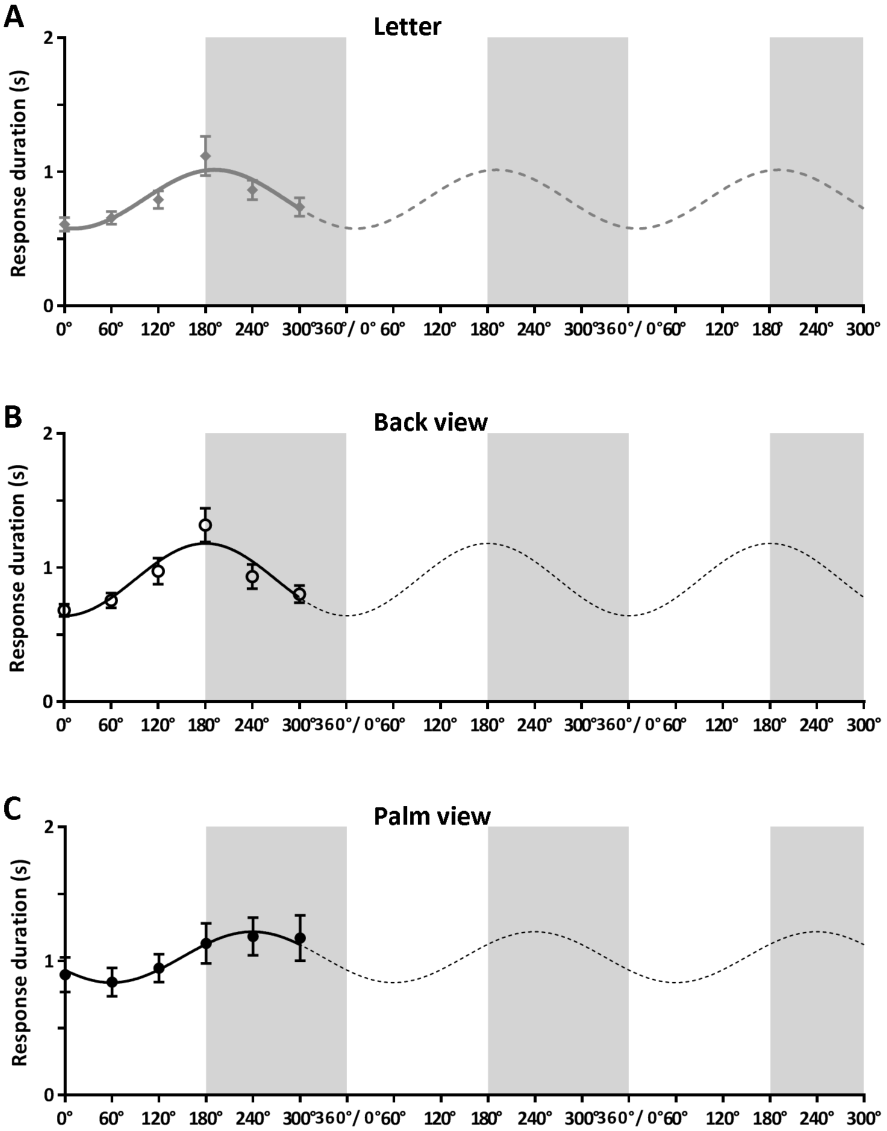
In sum, based on response accuracy, it is suggested that the ability to correctly perform the HLJ task increases with age. Notwithstanding these age-related differences, the response duration patterns indicated that when 5- to 8-year-olds successfully perform the HLJ task, they do this by using motor imagery. Although children do respond faster when they get older, notably, children's motor imagery strategy does not change with age between 5 and 8 years.

Appendix 3.1

Validation of the sinusoid models approach

To validate the a-priori defined predictive models, ten right-handed adults (mean age = 25.3 years; SD = 3.64; 3 male - 7 female) participated in an experiment that aimed to determine whether the a-priori models can indeed distinguish between non-motor and motor imagery strategies. The experimental procedure was similar to the procedure described in Chapter 3 ("Methods – Material and procedure"). In addition to the back and palm view stimuli, the adults also judged laterality of alphanumerical stimuli (the letter 'F'; one block of 36 trials [as was also described in Deconinck et al., 2009]). Block order was randomized. A group curve was fitted on the individual response duration patterns for the alphanumerical stimuli (letter) and for the hand stimuli (back and palm view) separately. These group fits were tested against the predictive models (H0, H1 and H2).

The alphanumerical data resulted in the following group model: Response duration (letter) = 0.219 * sin(angle – 101.6°) + 0.796. The fitted phase shift did not differ from 90° (H1), indicating that response durations were increasing as a function of increasing rotation angle (up to 180°; Appendix Figure 3.1A). In line with the expectation for mental rotation of non-body objects, this indicates that letters were judged using a non-motor imagery strategy. The following model was fitted on the back view data: Response duration (back view) = 0.270 * sin(angle – 90.4°) + 0.911. The fitted phase shift did not differ from 90°, indicating that direction of rotation did not affect response durations (Appendix Figure 3.1B). Adults used a non-motor imagery strategy to judge laterality of back view hands. The palm view data resulted in the following group model: Response duration (palm view) = 0.190 * sin(angle – 149.3°) + 1.028. For the palm view hands the fitted group phase shift did not differ from 180° (H2). Appendix Figure 3.1C illustrates the effect of direction of rotation, as the response durations are shorter for medial rotations and prolonged for lateral rotations. It was thus shown that adults use motor imagery to judge laterality of palm view hands. In sum, we were able to distinguish between non-motor (H1) and motor imagery (H2) strategies by means of the sinusoid models. This confirms the validity of the current sinusoid models as a method to determine whether participants use non-motor or motor imagery strategies on mental rotation tasks.



Appendix Figure 3.1. Response duration as a function of rotation angle. The solid lines represent the fitted sinusoid curves for the observed response durations (first wavelength). The dotted lines (second and third wavelengths) were added to better visualize the fitted curves. The data points in the first wavelength represent the mean response durations and standard error of means per rotation angle. Grey areas mark laterally rotated stimuli. *A*) Letters; *B*) Back view; *C*) Palm view.


4

Examining developmental changes in children's motor imagery: A longitudinal study

Manuscript submitted - Under review

Abstract

Using a longitudinal design, the present study examined developmental changes in the employment of (motor) imagery strategies on the hand laterality judgment task in children aged 5 to 7 years (n=23). Error percentages and response durations were compared to a-priori defined sinusoid models, representing different strategies to judge hand laterality. Response durations of correct and incorrect trials were included. Observed data showed that task performance was affected by motor constraints, both in children who performed accurately at 5 years of age and in the children who did not. This is the first study to show that 5-year-olds –even when not successful at the task– employ motor imagery when engaged in this task. Importantly, although the children became faster and more accurate across age, no developmental changes in the employed motor imagery strategy were observed between 5 and 7 years of age.

Motor imagery is a cognitive process during which people imagine performing a movement without any overt motor behaviour. As motor imagery comprises the internal activation of a movement representation from a first-person perspective, it shares many cognitive aspects with the actual execution of movements (Decety & Grezes, 1999; Jeannerod, 1995). The most frequently used paradigm to study motor imagery ability is the hand laterality judgment (HLJ) task. Within the HLJ task, participants judge whether a picture of a hand displays a left or a right hand. The combination of manipulating the angle of rotation (i.e., the degree to which the hand picture is rotated away from the upright position) and the direction of rotation (i.e., away or towards the midline of the body) defines the orientation of the hand stimulus. The angle of rotation can vary from 0° with the fingers pointing up to 180° with the fingers pointing down; the direction of rotation can vary between 90° with the fingers towards the midline of the body (medial orientation) and 270° with the fingers away from the body (lateral orientation; see Figure 4.1)

Participants can employ different (imagery) strategies to perform the HLJ task. We have recently introduced a-priori defined sinusoid models to determine what strategy participants employ when performing the HLJ task (Spruijt, Jongsma, van der Kamp, & Steenbergen, 2015). Specifically, the effects of varying rotation angle can be disentangled from the effects of varying direction of rotation on task performance (i.e., errors and response durations) as the observed data can be compared with the model-based predicted data to determine what strategy has been employed. Three possible strategies were discerned (Spruijt, Jongsma, et al., 2015). First, when HLJ task performance is not affected by rotation angle and/or rotation direction (the H0 hypothesis), participants do not systematically adopt a mental imagery strategy, but have likely relied on an abstract rule or used visual cues to judge the laterality of the presented hands (as suggested by ter Horst et al., 2010). Second, participants can mentally rotate the displayed hand like any other detached object to perform the HLJ task. This mental imagery strategy is not grounded in the motor system (i.e., non-motor imagery) and is indicated when only an effect of rotation angle is observed (the H1 hypothesis). This strategy would result in an often reported increase in response duration as a function of rotation angle (Shepard & Metzler, 1971). Third, when task performance is predominantly affected by manipulation of rotation direction, participants have most likely adopted a motor imagery strategy (the H2 hypothesis). Here, biomechanically 'awkward' hand orientations (i.e., lateral orientations) result in diminished task performance (i.e., more errors, longer response durations) compared to more 'comfortable' hand orientations (i.e., medial orientations) (Parsons, 1987).

In the current study, we examined developmental changes in children's employment of (motor) imagery strategies on the HLJ task. Thus far, motor imagery development has solely been studied by examining inter-individual age differences employing a cross-sectional approach (e.g., Butson et al., 2014; Caeyenberghs, Tsoupas, et al., 2009; Smits-Engelsman & Wilson, 2012; Spruijt, Jongsma, et al., 2015). As yet, motor imagery development has not been studied by using a longitudinal design that can reveal intra-individual changes over time (Spruijt, van der Kamp, & Steenbergen, 2015b). Such a design is however a critical initial step in capturing the dynamic processes of developmental change in motor ability and cognition (Grammer, Coffman, Ornstein, & Morrison, 2013; Thelen & Smith, 1994; Wohlwill, 1970).

With respect to changes in children's motor imagery as a function of age, previous cross-sectional studies using the HLJ task have shown equivocal results in children between 5 and 11 years of age. Krüger and Krist (2009) and Toussaint, Tahej, Thibaut, Possamai and Badets (2013) argued that the HLJ task performance was more constrained by motor characteristics for 7- vs. 5-year-olds (Krüger & Krist, 2009) and for 8- vs. 6-year-olds (Toussaint et al., 2013). These observations indicate increased motor imagery ability from 5 to 8 years of age. Butson, Hyde, Steenbergen and Williams (2014) also found age-related differences in motor imagery ability. However, their results do not suggest a consistent increase in motor imagery across age, as the results of the 8-, 9- and 11-year-olds did indicate the use of motor imagery, whereas the results of the 7- and 10-year-olds did not. Moreover, in a recent cross-sectional study, we did not observe any age-related differences in the use of motor imagery on the HLJ task between 5 and 8 years of age (Spruijt, Jongsma, et al., 2015).

A common facet of existing studies is the exclusion of erroneous responses and/or individual participants who do not perform the task sufficiently accurate (i.e., above chance level). This is especially evident in young children. As an illustration, Krüger and Krist (2009) excluded 40% of the 5-year-olds, and Butson et al. (2014) even excluded all children of 5 and 6 years old, as 73% of these children did not identify hand laterality above 50% accuracy. The ability of children to accurately judge hand laterality increases with age; for example, at 7 years of age only 17% of the children were not able to perform the task above chance levels in the study of Krüger and Krist (2009). Importantly, however, with the exclusion of inaccurately performing children and erroneous trials, it is likely that insights in the early development of (motor) imagery strategies are biased or overlooked. Specifically, the transition from not performing the task above chance to performing the task above chance may indicate developmental changes in motor imagery that are potentially overlooked if only participants are included that perform the task accurately. Children that perform the task inaccurately might thus have different developmental trajectories than children performing accurately. So far, it remains unclear whether young children perform the task inaccurately due to an inability to understand the task instructions or other limitations in cognitive ability, an inability to employ motor imagery or inaccuracy while employing motor imagery. Therefore, in addition to examining developmental changes in the strategies employed by the children performing above chance, we also analyzed imagery strategies of children that did not perform above chance.

Following the approach of our previous cross-sectional study (Spruijt, Jongsma, et al., 2015), we determined the employed strategies by examining the effects of task manipulations on response accuracy and response duration patterns via a longitudinal design, including the data from all erroneous responses. With respect to erroneous responses, we predict that similar effects as commonly described for the response durations can be observed. Hence, we hypothesize that when children perform the HLJ task at chance, this might be due to an inability to understand the task. For instance, when children cannot discriminate the concepts left from right they will perform misguided or blind guesses, instead of performing genuine judgments of hand laterality. If this is the case, then the amount of erroneous responses would not be systematically affected by stimulus manipulations (H0). Alternatively, it might also be that children who do not perform above chance level do use mental imagery, but not fully master the employed strategy. If, for example, children produce more erroneous responses on stimuli with larger rotation angles compared to smaller rotation angles (effect of angle of rotation; H1), this would suggest a non-motor imagery strategy to perform the task. In contrast, if stimuli with lateral orientations result in more erroneous responses than medial orientations (direction effect; H2), this would suggest a motor imagery strategy.

In the present study, we aim to determine early developmental changes in the employment of (motor) imagery strategies on the HLJ task, for children performing the task at chance and above chance at 5 years of age. We included children that were 5 years old and followed them longitudinally for three consecutive years to determine whether and how the involvement of imagery strategies on the HLJ task changes at 5, 6 and 7 years of age. This age range was shown to be critical with respect to age-related differences in the ability to accurately perform the HLJ task and age-related differences in motor imagery (e.g., Butson et al., 2014; Caeyenberghs, Tsoupas, et al., 2009; Smits-Engelsman & Wilson, 2012), which can be related to the maturation of cognitive processes that are involved in motor imagery during childhood (Caeyenberghs, Wilson, et al., 2009). In line with our previous cross-sectional results (Spruijt, Jongsma, et al., 2015), we expect that the response durations of children performing the HLJ task above chance are affected by motor constraints (direction effect; H2) between 5 and 7 years of age. In this group, we do not expect developmental changes in the use of the motor imagery strategy. As we are the first to address motor imagery ability in children who do not perform the HLJ task above chance, we explore whether children who are inaccurate at the task at 5 years of age are engaged in motor imagery, via the examination of response accuracy patterns. Furthermore, we explore whether developmental changes in the employed strategies underlie anticipated improvements in overall HLJ task accuracy between 5 and 7 years of age (see Butson et al., 2014).

Methods

Participants

A total of 23 typically developing right-handed children participated in the study (11 male). The participants were 5 years of age at the moment of the first measurement (mean age = 5.60 year; SD = 0.249). Parents provided written informed consent prior to the experiment. The study was approved by the local ethics committee (ECG2012-2402-018). The response duration data of the correct trials from the first measurement was already used in our previous cross-sectional study (Chapter 3).

Material and procedure

The experimental procedure is similar to the procedure described in our previous study (for details, see Spruijt, Jongsma, et al., 2015). Children had to judge whether a picture, which was presented on a computer screen, displayed a left or a right hand. After a white fixation cross was presented, a picture of a hand was shown in the middle of the screen. The child was instructed to press a button with the left hand for a picture of the left hand, and with the right hand for a picture of the right hand. The children were instructed to respond as fast as possible. The picture disappeared after the response was given and the fixation cross was shown until the next stimulus presentation. The children were not allowed to make any hand and/or head rotations during the laterality judgment and the hands were covered with a cloth to prevent a direct visual comparison.

The stimuli were pictures of left and right hands, showing the palm of the hand. The stimuli were presented in six different rotation angles: 0°; 60°; 120°; 180°; 240°; 300° (Figure 4.1). Hands with the fingers pointing upwards were defined as stimuli with a rotation angle of 0°, stimuli with a rotation angle of 180° displayed the hand with the fingers pointing down. Medial rotations were represented by stimuli with rotation angles between 0° and 180° and lateral rotations were represented by stimuli with rotation angles between 180° and 360°. Each hand stimulus was presented three times, resulting in 36 randomly ordered trials. Six practice trials were performed before the start of the experiment. The study employed a three-year longitudinal design during which the participants were measured annually.

Data analysis

A binomial distribution (p = 0.50 for each trial) was used to establish whether or not the children performed the HLJ task above chance level. Individual performance was significantly above chance level when more than 23 out of 36 stimuli were correctly identified. Based on the task accuracy at 5 years of age, we divided the children in two groups; a group of children that was not able to perform the HLJ task above chance level at 5 years of age (Group A) and a group of children that was able to perform the HLJ task above chance level at 5 years of age (Group B). It was determined whether age (3;

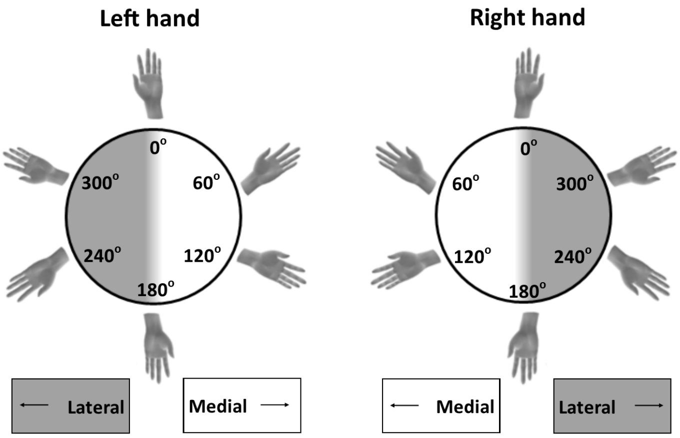


Figure 4.1. Examples of hand stimuli. Hand stimuli consist of left and right hands in the palm view, varying in rotation angle and direction of rotation.

within-subjects factor) and group (2; between-subjects factor) affected the percentage of erroneous responses by means of a repeated measures ANOVA.

For the response durations, outlier trials (response duration < 250 ms or response duration > mean response duration + 3*standard deviation) were excluded from further analyses (1.93% of the trials). Percentages of erroneous responses and response durations for left and right hand stimuli were pooled and averaged across the repetitions of each of the six rotation angles. To determine the strategy that participants of Group A and B employed at each age, the averaged observed data were compared to the hypothetical models (see Spruijt, Jongsma, et al., 2015). Error and response duration data were analyzed separately. Goodness of fit F-tests were used to model the distribution of the data as a function of the rotation angle and the direction of rotation in GraphPad Prism 6. It was tested whether the amplitudes differed from 0 (H0; non-imagery strategy) at each age. If H0 was rejected, it was tested whether the phase shift was different from 90° or not (H1; phase shift = 90°, a non-motor imagery strategy was employed) and whether the phase shift was different from 180° or not (H2; phase shift > 90° and ≤ 180°, a motor imagery strategy was employed). A Bonferroni correction was used that resulted in an alpha level of $p = 0.017$ (three measurements).

To examine whether imagery strategies changed across age, F-tests for goodness of fit (GraphPad Prism 6) were used to determine whether the error and response duration data at 5, 6 and 7 years old could be described by the same parameters. This analysis was performed for Group A and B separately.

Results

Response accuracy (error percentage)

15 (8 male) out of 23 children did not perform the HLJ task above chance at 5 years of age. These children were assigned to Group A (mean age = 5.51; SD = 0.248). Only three of these children were not able to accurately perform the HLJ task at age 6 and one of them still did not perform above chance at 7 years of age. Group B (mean age = 5.76; SD = 0.171) consisted of 8 children (3 male) that were already able to perform the HLJ task above chance at 5 years of age. One of them did not perform above chance at 6 and 7 years of age.

We described the variation in percentage of erroneous responses as a function of rotation angle and direction in Group A and B by means of sinusoid curves and tested them to the three a-priori defined sinusoid models that reflect the different strategies to perform the HLJ task. The resulting parameters of the sinusoid curves are displayed in Table 4.1 and the curves are presented in Figure 4.2. For example, the error data for Group A at 5 years of age could best be described by *percentage error = 16.5*sin(angle-198)+ 51.3*.

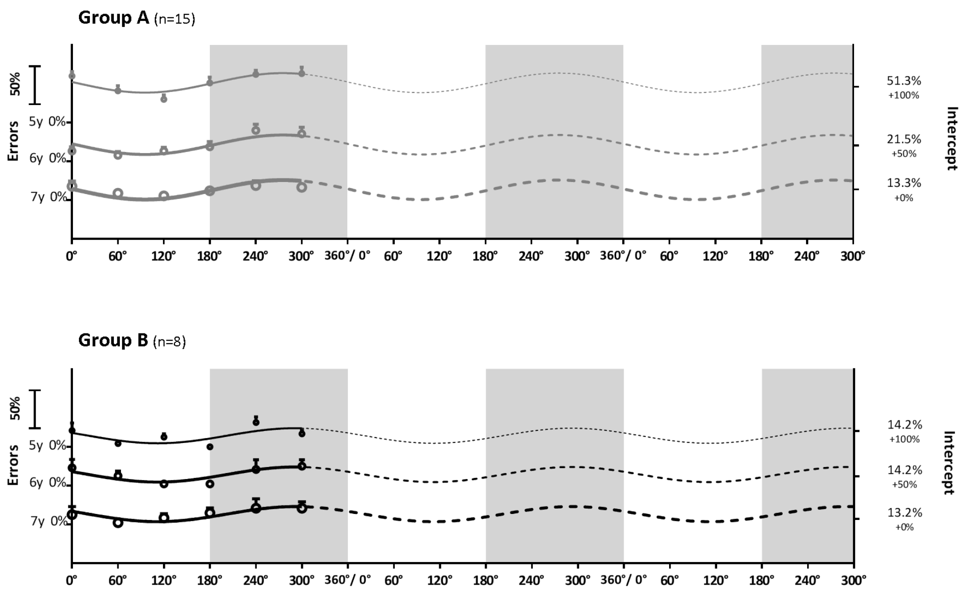


Figure 4.2. Percentage of erroneous responses as a function of rotation angle. The solid lines represent the sinusoid curves through the observed error percentages. The dotted lines were added to depict the sinusoid nature of the a-priori defined models. For better visualization, the curves are transposed as indicated on the right y-axis (5 years +100%; 6 years +50%; 7 years +0%). The data points present the mean percentage of errors and the standard error of the means per rotation angle. Grey areas represent laterally rotated stimuli.

Table 4.1

Fitted parameters on the erroneous response data (standard error) for Group A and B

	Group A			**Group B**		
	Amplitude	*Phase shift*	*Intercept*	*Amplitude*	*Phase shift*	*Intercept*
Age 5	16.5 (3.81)	198 (13.2)	51.3 (2.69)	9.55 (3.59)	199 (21.5)	14.2 (2.54)
Age 6	16.1 (3.77)	167 (13.4)	21.5 (2.67)	13.0 (4.52)	226 (19.9)	14.2 (3.20)
Age 7	6.43 (2.91)	198 (26.0)	13.3 (2.06)	9.19 (4.55)	169 (28.4)	13.2 (3.22)

The amplitudes of the sinusoid curves (Table 4.1) were significantly larger than 0 for children of 5 and 6 years old, both for Group A and B (see Table 4.2; reject the H0 hypothesis), indicating that the amount of errors varied as a function of rotation angle and/or direction of rotation. The H0 hypothesis was not rejected for the children at age 7, so the H1 and H2 hypotheses were not tested at this age. However, at age 5 and 6 for Group A and at age 5 for Group B, the phase shift parameters (Table 4.1) were significantly larger than 90° (reject the H1 hypothesis), but did not differ from 180° (consistent with the H2 hypothesis; Table 4.2). At these ages, response accuracy was thus shown to be affected by motor constraints, as evidenced by high number of errors for judging laterally rotated hands, compared to fewer mistakes for judging medially rotated hands (see Figure 4.2). Therefore, motor imagery employment was indicated in these children, even when making incorrect judgments.

Table 4.2

F-tests of goodness of fit for the fitted parameters on the percentage of errors

	Fitted parameter tested against	**Group A**			**Group B**		
		***F* (1,87)**	***p***	η^2	***F* (1,45)**	***p***	η^2
Age 5	Amplitude ≈ 0	18.8	0.000*	0.402	7.09	0.0107*	0.202
	Phase shift = 90	17.0	0.000*	0.378	6.31	0.0156*	0.184
	Phase shift = 180	1.72	0.193	0.0579	0.758	0.3886	0.0263
Age 6	Amplitude ≈ 0	18.2	0.000*	0.394	8.30	0.006*	0.229
	Phase shift = 90	17.4	0.000*	0.383	3.99	0.0519	0.125
	Phase shift = 180	0.870	0.353	0.0302	4.31	0.0437	0.134
Age 7	Amplitude ≈ 0	4.88	0.0299	0.148	3.90	0.0544	0.122
	Phase shift = 90	#	#	#	#	#	#
	Phase shift = 180	#	#	#	#	#	#

** Significant (p < 0.017; Bonferroni corrected)*

 # Phase shift = 90 and phase shift = 180 were not tested when the amplitude did not differ from 0.

To examine developmental changes in employed strategies, we tested whether the parameters of the sinusoid curves describing the data changed across age. The amplitude and phase shift parameters did not change across age, indicating that the employed strategy remained similar between 5 and 7 years of age. However, it was found that the intercept parameters of Group A did change across age (F(2,261) = 64.39, $p < 0.0001$, $\eta^2 = 0.404$). This exemplifies a decrease in the average percentage of errors across age (i.e., from 51.3% at age 5, to 13.3% at age 7, see Table 4.1). For Group B, none of the parameters changed between ages 5, 6 and 7, indicating that not only the employed strategies were constant over age, but also the amount of errors (see Table 4.1).

Response duration

For each age separately, response duration data of Group A and B were fitted to a-priori defined models that describe response duration patterns for different strategies. Table 4.3 presents the resulting fit equations and Figure 4.3 presents the complementary curves that were fitted on the response duration data for Group A and B.

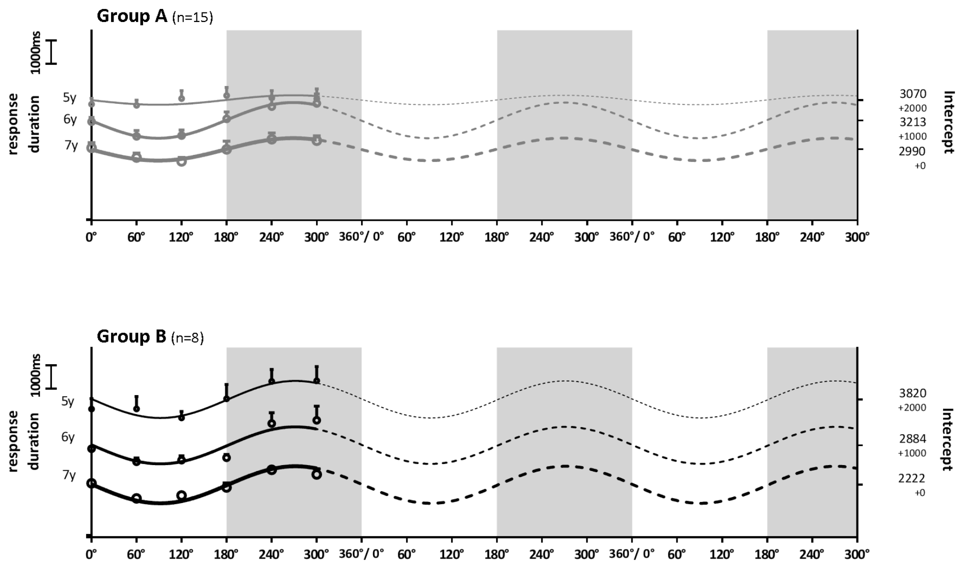


Figure 4.3. Response duration as a function of rotation angle. The solid lines represent the sinusoid curves through the observed response durations. The dotted lines were added to depict the sinusoid nature of the a-priori defined models. For better visualization, the curves are transposed as indicated on the right y-axis (5 years +2000; 6 years +1000; 7 years +0). The data points present the mean percentage of errors and the standard error of the means per rotation angle. Grey areas represent laterally rotated stimuli.

Table 4.3

Fitted parameters on the response durations (standard error) of Group A and B

	Group A			Group B		
	Amplitude	*Phase shift*	*Intercept*	*Amplitude*	*Phase shift*	*Intercept*
Age 5	199 (179)	118 (51.6)	3070 (127)	790 (285)	174 (20.7)	3820 (201)
Age 6	753 (165)	178 (12.6)	3213 (117)	960 (192)	188 (11.5)	2884 (136)
Age 7	475 (138)	185 (16.6)	2990 (97.6)	605 (92.4)	181 (8.76)	2222 (65.3)

With the exception of the children in Group A at 5 years of age, the amplitude parameters (Table 4.3) were significantly larger than 0 in both groups at all ages (Table 4.4; reject the H0 hypothesis). Hence, except for children of Group A at 5 years of age when they all performed inaccurately, response durations varied as a function of rotation angle and/or direction of rotation (see Figure 4.3). The phase shift parameters (Table 4.3) were significantly larger than 90° (reject the H1 hypothesis), but they did not significantly differ from 180° (consistent with the H2 hypothesis; Table 4.4). Figure 4.3 illustrates this effect of direction of rotation, as the response durations for judging hands reached a maximum for laterally rotated hands (rotation angle of approximately 270°) and the durations are minimum for medially rotated hands (rotation angle of approximately 90°). These results thus provide indications for the use of motor imagery.

Table 4.4

F-tests of goodness of fit for the fitted parameters on the response durations

	Fitted parameter tested against	Group A			Group B		
		$F_{(1,87)}$	p	η^2	$F_{(1,45)}$	p	η^2
Age 5	Amplitude ≈ 0	1.22	0.273	0.0417	7.67	0.0081*	0.354
	Phase shift = 90	#	#	#	7.62	0.0083*	0.353
	Phase shift = 180	#	#	#	0.0740	0.787	0.0052
Age 6	Amplitude ≈ 0	20.8	0.000*	0.426	25.0	0.000*	0.641
	Phase shift = 90	20.8	0.000*	0.426	24.4	0.000*	0.636
	Phase shift = 180	0.0203	0.887	0.0072	0.527	0.472	0.036
Age 7	Amplitude ≈ 0	11.9	0.0009*	0.298	43.0	0.000*	0.754
	Phase shift = 90	11.8	0.0009*	0.296	42.8	0.000*	0.754
	Phase shift = 180	0.0762	0.783	0.0027	0.004	0.950	0.0003

** Significant ($p < 0.017$; Bonferroni corrected)*

 # Phase shift = 90 and phase shift = 180 were not tested when the amplitude did not differ from 0.

The amplitude parameters of Group A changed across age ($F(2,261) = 13.83$, $p < 0.0001$, $\eta^2 = 0.429$). However, the phase-shift parameters did not change across age. Put differently, direction of rotation predominantly affected the response durations in all three age groups, but the degree to which the direction of rotation affected the response duration differed across age. The intercepts also changed with age ($F(2,261) = 82.79$, $p < 0.0001$, $\eta^2 = 0.422$). Noteworthy, the response durations did not display an ongoing decrease as a function of age, a durations were shorter at age 5 than at age 6 (see Table 4.3 and Figure 4.3). For Group B, the amplitude and phase shift parameters did not change between ages 5, 6 and 7, indicating that the employed strategies were similar at these ages. The intercept changed with age ($F(2,135) = 30.55$, $p < 0.0001$, $\eta^2 = 0.426$), indicating that the children did become faster from 5 to 7 years of age (see Table 4.3 and Figure 4.3).

Discussion

In the present study, we examined the employment of motor imagery strategies on the HLJ task in children between 5 and 7 years of age. Children that performed the HLJ task at chance have conventionally been excluded from further analyses in previous studies (Butson et al., 2014; Funk et al., 2005; Krüger & Krist, 2009; Spruijt, Jongsma, et al., 2015). However, exclusion of children who do not judge hand laterality above chance might obscure a deeper insight into early developmental changes in imagery strategies. Therefore, we included children that performed at chance on the HLJ task at 5 years of age and examined the developmental changes in their performance, in addition to examining the children that did perform above chance at age 5. Since previous cross-sectional studies have not provided an unequivocal description of employed motor imagery strategies across age, we aimed at examining developmental changes in children's motor imagery strategies by using a longitudinal design over a period of three years. In what follows, we first discuss if overall HLJ task performance improved with age in terms of accuracy and response speed in both groups. Second, we discuss whether the error patterns, and whether the response duration patterns were random or whether they were according to a-priori defined sinusoid models that reflect imagery strategies (see also Spruijt, Jongsma, et al., 2015). This was examined both for the children performing at and above chance at age 5. Finally, we discuss whether developmental changes in employed strategies can explain age-related improvements on the HLJ task performance.

The overall HLJ task performance improved across age in children of both groups. The children that were already able to accurately judge hand laterality at age 5 (Group B) became faster at judging hand laterality across age, as evidenced by developmental changes in the intercept of the sinusoid curves for the response durations (see also Caeyenberghs, Tsoupas, et al., 2009; Spruijt, Jongsma, et al., 2015). Task accuracy, however, did not change across three consecutive years, as was illustrated by the consistently low percentage of errors at age 5, 6 and 7 (approximately 14%, see Table 4.2). In contrast, children who did not perform the task accurately at age 5 (Group A) showed significant improvements on task accuracy and response speed between 5 and 7 years of age. Most of these children underwent a transition from not performing the task above chance at age 5, to performing the task above chance at the ages of 6 and 7.

We first discuss developmental changes in employed imagery strategies for the children that were already accurate at age 5, that is, above chance level (only one third of the children; Group B). It is important to note that for studying children who perform above chance, because of their low number of errors, the error data is less reliable for drawing conclusions concerning the employed imagery strategies. Therefore, we focus on the response duration results in these children. The pattern of response durations was affected by motor constraints at age 5, 6 and 7, indicating that children employed motor imagery. Importantly, the amplitude and phase shift did not differ across age. In line with our previous cross-sectional study, these longitudinal results thus confirm that the employed motor imagery strategy does not show developmental changes for children that accurately perform the HLJ task between 5 and 7 years of age (Spruijt, Jongsma, et al., 2015). These findings however diverge from previous studies that have shown age-related increases in motor imagery capability in children between 5 and 8 years of age (Krüger & Krist, 2009; Toussaint et al., 2013). Apart from differences in design (cross-sectional vs. longitudinal) and differences in the stimulus sets (among these are back and/or palm view stimuli and different angles of rotation), a likely reason for the differences in study results is the analysis methods for determining the employed strategies based on the response duration and response accuracy data. Whereas most previous studies separately considered the effect of rotation angle and direction of rotations (e.g., Funk et al., 2005; Krüger & Krist, 2009; Toussaint et al., 2013), the current approach considers the cumulative effects of these factors (see also Spruijt, Jongsma, et al., 2015).

Previous HLJ task studies excluded children who performed at chance from further analyses, without discussing the underlying reason for doing so (Butson et al., 2014; Funk et al., 2005; Krüger & Krist, 2009; Spruijt, Jongsma, et al., 2015). The exclusion of these children suggests that researchers (perhaps implicitly) interpreted this as a lack of ability to use motor imagery. As a critical extension of these studies, we also examined the employed motor imagery strategies for children that did not perform above chance at 5 years of age. Before considering developmental changes in imagery strategies in these children, we first address the question whether inaccurate performance on the HLJ task is indeed caused by an inability to employ motor imagery (see Deconinck et al., 2009; Williams et al., 2008). Alternatively, an inability to understand task instructions or inaccuracy while employing motor imagery can underlie inaccurate HLJ task performance. In line with Butson et al. (2014), the majority of 5-year-old participants did not perform above chance. It is important to note that for studying the employed strategies in children who did not perform above chance, the error data might be more reliable than response duration data. That is, in line with the speed-accuracy trade-off, the 5-year-olds who responded at chance (high numbers of errors; Group A) responded relatively fast in comparison with their peers who performed accurately (Group B; see Table 4.3 and Figure 4.3). Because of these fast responses and concomitant low accuracy, we propose that the error data are more representative of the employed imagery strategies compared to the response duration data. It was found that task accuracy, that is the error pattern, was clearly affected by motor constraints in children performing at chance at age 5. Hand stimuli representing biomechanically less awkward (medial) rotations more often led to correct responses than those with more awkward (lateral) rotations, indicating the use of motor imagery (see also ter Horst et al., 2010). We can therefore reject the hypothesis that the children did not understand the HLJ task, which would have resulted in blind guesses (i.e., no structure in the pattern of errors) to perform the task (see also Mutsaarts, Steenbergen, & Bekkering, 2007). It can thus be concluded that even though children perform the HLJ task inaccurately at young age, they already have mental representations of hand movements and are able to access them for judging hand laterality. Hence, involvement of motor imagery is not the rate limiter (the slowest developing factor that affects how well an individual can exhibit a motor behaviour, see Thelen & Smith, 1994) for accurately performing hand laterality judgments. Alternatively, more general cognitive abilities might hinder HLJ task performance (see Spruijt, Jongsma, et al., 2015). For instance, attention might be a rate limiter for the HLJ task at young age, because judging hand laterality through the internal activation of mental representations of hand movements has been suggested to place large demands on children's attention (Schott, 2012).

Determining developmental changes in employed strategies is particularly of interest in children of Group A, as most of these children underwent a transition from not performing the task above chance at age 5, towards performing the task above chance at age 6 and 7. Yet, we did not observe developmental changes in the strategy that the children employed at age 5, 6 and 7. In the above, we already discussed that response accuracy patterns indicated motor imagery involvement at age 5. At age 6 and 7 (most children then performed above chance) response durations were largest for stimuli in biomechanically awkward (lateral) rotations, indicating the use of motor imagery (see also ter Horst et al., 2010). Furthermore, we found that the phase shifts for the sinusoid curves of Group A did not vary as a function of age, neither for the error data, nor for the response duration data. Hence, no developmental changes in the employed motor imagery strategies did not display developmental changes were observed between 5 and 7 years of age. Consequently, the observed improvements in overall performance on the HLJ task (faster and more accurate responses) in young children cannot be attributed to developmental changes in the employed motor imagery strategy to perform the HLJ task. Instead, we argue that HLJ task improvements might be attributed to the development of cognitive abilities that can influence HLJ task performance during childhood. As was already discussed, the process of mentally representing hand movements in order to judge hand laterality places large demands on children's attention (Schott, 2012). HLJ task improvements between 5 and 7 years of age might therefore be linked to improvements in attention processes across age (Breckenridge, Braddick, & Atkinson, 2013; Levy, 1980). In a similar fashion, as motor imagery involves activation of movement representations in working memory (Decety & Grezes, 1999; Munzert et al., 2009), working memory capacity might affect hand laterality judgments (see also Gabbard et al., 2013; Schott, 2012). Since working memory is developing during childhood (Kemps, De Rammelaere, & Desmet, 2000), these developmental changes might underlie the improvements on the HLJ task between 5 and 7 years of age.

To conclude, children's HLJ task performance is affected by motor constraints at age 5. Motor representations that are involved in the planning and feedforward control of movement (Jeannerod, 1994; Vogt et al., 2013; Wolpert, 1997) are thus formed and can already be accessed at 5 years of age. This accords well with previous indications that the majority of 5-year-old children are able to plan their movements (Weigelt & Schack, 2010) and use feedforward control (De Ste Croix & Korff, 2012). In order to examine the early development of motor imagery, we extended previous studies by additionally examining the large proportion of children that did not perform above chance level at the HLJ task at age 5. We observed that children were engaged in motor imagery to perform the HLJ task, even when this led to a high proportion of erroneous responses. We thereby demonstrate that motor imagery ability is not the limiting factor for accurate HLJ task performance. Furthermore, the use of motor imagery to judge hand laterality did not change across age between 5 and 7 years, neither for the children who performed consistently accurate (in accordance with our previous cross-sectional findings), nor for the children who were not accurate at age 5. Consequently, it can be concluded that once children are able to activate movement representations, the use of this motor imagery strategy for performing the HLJ task does not change across age. The improvements in accuracy and speed on the HLJ task across age can therefore not be attributed to developmental changes in the use of motor imagery. Alternatively, the development of more general cognitive processes like working memory and attention might underlie the development of children's HLJ task performance.


5

The ability of 6- to 8-year-old children to use motor imagery in a goal-directed pointing task

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Abstract

It has been suggested that motor imagery ability develops gradually between 5 and 12 years of age, but ambiguity remains over the precise developmental course before 9 years of age. Hence, we determined the age-related differences in the use of motor imagery by children on the mental chronometry paradigm. In addition, we examined whether the use of motor imagery is related to cognitive and hand abilities. To this end, we compared duration of actual pointing and imagined pointing on a radial Fitts' task in 82 children (three age groups; 6-, 7- and 8-year-olds). In line with previous studies, we found an age-related increase in temporal congruence between actual and imagined pointing and compliance with Fitts' law. Importantly, however, we showed that only a limited number of 7- and 8-year-olds were actually using motor imagery to perform the imagined pointing task, whereas the 6-year-olds did not employ motor imagery to perform the task. The current results extend previous research by establishing that the age of onset to use motor imagery in the mental chronometry paradigm is not prior to 7 years of age.

In motor imagery, people imagine themselves moving without actually performing the action. Motor imagery entails the internal activation of a first person movement representation in working memory devoid of any overt motor output (Decety & Grezes, 1999). Jeannerod (1994) argued that motor imagery and motor preparation are functionally equivalent, as they both rely on the same movement representation. Therefore, imagining a movement is predicted to be subject to similar task constraints as motor performance (Decety et al., 1989; Jeannerod, 1995; Lotze & Halsband, 2006).

Mental chronometry is a frequently used experimental paradigm to determine motor imagery ability. Mental chronometry examines whether performing and imagining the same movement corresponds with respect to duration. This temporal congruence between actual and imagined movement performance was indeed shown in studies that used walking or pointing to a target (Bakker et al., 2007; Caeyenberghs, Wilson, et al., 2009; Cerritelli et al., 2000; Choudhury et al., 2007a; Decety et al., 1989; Molina et al., 2008; Papaxanthis, Pozzo, Skoura, & Schieppati, 2002). Yet, can be argued that finding temporal congruence alone is sufficient to conclude that participants actually use motor imagery. Temporal congruence can also be the consequence of alternative strategies, including the use of memories of movement performance, estimates of task duration by counting, or visual imagery, in which a movement is typically imagined from a third person perspective (Cerritelli et al., 2000; Malouin, Richards, Durand, & Doyon, 2008; Munzert et al., 2009). Therefore, to establish that motor imagery is used instead of alternative strategies, additional criteria need to be fulfilled. Specifically, as motor imagery is grounded in motor control processes, the pattern of imagined durations should be subject to the same motor constraints as the performance of actual movements (Currie & Ravenscroft, 1997). Thus, to be sure that participants enlist motor imagery and not alternative non-motor strategies, it needs to be verified that imagined performance complies with the same motor constraints as movement performance (Sirigu et al., 1996).

One way to verify the use of motor imagery within the mental chronometry paradigm is to systematically manipulate task difficulty and examine its effect on both actual and imagined movement performance. Actual pointing movements are commonly found to comply with Fitts' law, in which movement duration is lawfully related to task difficulty (movement duration = a + b * index of difficulty, with index of difficulty = log2 (2 * distance / width) (Fitts, 1954)). Task difficulty is manipulated via systematic manipulation of target width and/or target distance. Consequently, Fitts' tasks are frequently used within the mental chronometry paradigm to study the effect of systematically manipulating task difficulty on actual and imagined movement performance (Cerritelli et al., 2000; Choudhury et al., 2007a; Wilson et al., 2001). Participants perform repetitive pointing movements towards a series of targets, both by actually performing these movements and by imagining these movements. Based on

Fitts' law, the same lawful relation between on the one hand duration and on the other hand task difficulty is anticipated for the actual and imagined pointing performance if they emerge from the same (motor) constraints. Indeed, previous research in adults has not only shown temporal congruence, but also compliance with Fitts' law during both actual and imagined pointing performance (Cerritelli et al., 2000; Choudhury et al., 2007a; Sirigu et al., 1996). From this it can be concluded that motor imagery contributes to performing the mental chronometry paradigm.

Studies on motor imagery are widespread in the adult population, but only a limited number of studies have examined motor imagery in children. These studies suggest that the capability for motor imagery gradually develops between 5 and 12 years of age (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Hoyek et al., 2009; Molina et al., 2008; Skoura et al., 2009; Smits-Engelsman & Wilson, 2012). Three studies based this suggestion on the analysis of temporal congruence alone, without a systematic manipulation of motor constraints (Hoyek et al., 2009; Molina et al., 2008; Skoura et al., 2009). Three other studies complemented the analyses by examining whether temporal congruence between the actual and imagined pointing performance arises from the same motor constraints (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012). Generally, these three studies indeed confirm that both temporal congruence (i.e., the correlation between the duration of actual and imagined movement performance) and compliance with Fitts' law (i.e., task difficulty linearly affects durations of actual and imagined movement performance) increase with age in 5- to 12-year-old children (Table 5.1). This developmental trajectory was derived from a direct comparison *between* groups of 5- to 8- and 11- to 12-year-old children. However, detailed scrutiny of the findings also suggests that reported effects of task difficulty on imagined performance *within* the group of 5- to 8-year-olds showed a few discrepancies. On the one hand, Smits-Engelsman and Wilson (2012) found that imagery performance within a group of 5- to 7-year-olds was not affected by task difficulty and did therefore not comply with Fitts' law. On the other hand, results by Caeyenberghs, Tsoupas et al. (2009) and Caeyenberghs, Wilson et al. (2009) suggested that within a group of 6- and 7-year-olds and a group of 7- and 8-year-olds, respectively, imagined performance did comply with Fitts' law, although only weakly (Table 5.1). The discrepancies in these studies may originate from groups with slightly different age range, as well as from the different methods in assessing whether or not the criteria for the use of motor imagery are satisfied. The current study focused on comparing the ability of 6-, 7, and 8-year-olds to use motor imagery, as previous studies suggest that within this age range critical changes occur in the use of motor imagery.

Table 5.1

Age differences in imagined durations on Fitts' tasks, as reported by previous studies

	Caeyenberghs, Tsoupas et al. (2009)	**Caeyenberghs, Wilson et al. (2009)**	**Smits-Engelsman and Wilson (2012)**
Age groups	1: 7-8 2: 9-10 3: 11-12	1: 6-7 2: 8-9 3: 10-11 4: 12-13 5: 14-16	1: 5-7 2: 8-10 3: 11-13 4: 14-19 5: 20-29
Temporal congruence [a]	1 vs. 2 and 3	1 vs. 4 and 5 2 vs. 4 and 5	1 vs. 2, 3, 4 and 5 2 vs. 4 and 5
Task difficulty [b]	not reported	1 vs. 2, 3, 4 and 5	no effect in 1 and 2
Fitts' law [c]	1 vs. 2 and 3	1 vs. 3, 4 and 5 2 vs. 5	not reported

[a] Age differences for the correlation between imagined and performed durations

[b] Age differences for index of difficulty on imagined durations

[c] Age differences for goodness of linear fit between index of difficulty and imagined durations

The three previous studies (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012) primarily aimed at charting differences between age groups in the degree to which they showed temporal congruence and compliance with Fitts' law. This is one pertinent step. However, a second important step is to determine whether or not the performance of each single age group can also be reliably distinguished from non-congruence and non-compliance (i.e., confirming that the resulting correlations and linear regressions differ from zero). If so, this would considerably strengthen the conclusion that the age group used motor imagery when imagining movement performance. Previous work did not take this second step; analyses were restricted to comparisons between age groups. Hence, we compared the degree to which durations for actual and imagined pointing show temporal congruence and compliance with Fitts' law in groups of 6-, 7- and 8-year-olds on a radial Fitts' task. We additionally set out to assess whether or not these two criteria for the use of motor imagery are satisfied for children in each age group separately. To reiterate, by examining 6-, 7- and 8-year-olds, we hoped to further clarify the early development of the use of motor imagery in performance on the mental chronometry paradigm.

Children's development of motor imagery ability may be related to significant developmental changes in the cognitive and motor domain. Both structural and functional changes in brain development are evident during childhood (Casey, Tottenham, Liston, & Durston, 2005). Children's neurological development is accompanied by extensive development in the cognitive and motor domain. That is, several studies indicate pronounced changes in cognitive processes associated with executive functioning. For instance, inhibitory control markedly improves between 6 and 8 years of age (Brocki & Bohlin, 2004; Ikeda, Okuzumi, & Kokubun, 2014). These developmental changes in 6- to 8-year-olds were also shown for motor planning (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Craje, & Steenbergen, 2013; Stockel, Hughes, & Schack, 2012) and motor skill (as reflected by hand ability; Brito & Santos-Morales, 2002; Jongbloed-Pereboom, Nijhuis-van der Sanden, & Steenbergen, 2013).

Hence, the current study also examined the cognitive and motor factors that are likely to affect the motor imagery ability in these children. First, in light of behavioural and neurophysiological relations between actual and imagined movement performance, it has often been argued that the ability to enlist motor imagery is related to motor ability (de Lange, Roelofs, & Toni, 2008; Decety et al., 1989; Lorey et al., 2010; Munzert et al., 2009; Parsons, 1987; Wilson et al., 2001). In support, two studies reported that motor skill (i.e., measured by the McCarron Assessment of Neuromuscular Development) and fine hand skills (i.e., measured by 2 subtests of the Movement-ABC2) significantly correlated with motor imagery performance across groups of participants ranging between 5 and 29 years of age (Smits-Engelsman & Wilson, 2012), although not in children younger than 11 years of age (Caeyenberghs, Tsoupas, et al., 2009). Second, as motor imagery is a form of motor *cognition* (Jeannerod, 2001), its development is conceptually related to the development of cognitive abilities, in particular executive function (e.g., working memory, inhibition, attention) (see also Krüger & Krist, 2009). Because motor imagery is a motor process in which the actual movement is inhibited (Decety, 1996b; Guillot et al., 2012; Jeannerod, 2001), the development of inhibitory control during childhood may be associated with the development of motor imagery. Hence, as a secondary aim, we explored the relationship between motor imagery ability, on the one hand, and motor ability (i.e., hand ability) and cognitive ability (i.e., inhibition), on the other.

Methods

Participants

Right-handed participants were recruited from mainstream primary schools. The 82 typically developing children were divided in three age groups: 6 years old (5.51-6.50), 7 years old (6.51-7.50) and 8 years old (7.51-8.50). A group of 22 adult participants was included as a reference group. They were recruited at the university, and between 18 and 25 years old. Mean age and gender for all participant groups are displayed in Table 5.2. Prior to the experiment, children's parents and the adult participants provided written informed consent. The study was approved by the local ethics committee.

Table 5.2

Characteristics of participant groups

Age group	**Mean age (SD) in years**	**Gender (n male/ n female)**
6-year-olds (n=28)	5.98 (0.05)	12 / 16
7-year-olds (n=28)	7.03 (0.51)	13 / 15
8-year-olds (n=26)	7.98 (0.06)	12 / 14
Adults (n=22)	19.6 (1.9)	3 / 19

Material and procedure

The children performed the radial Fitts' task and the cognitive and the hand ability tests in a random order. Adults only performed the motor imagery task.

Radial Fitts' task

Motor imagery was assessed using a radial Fitts' task (Caeyenberghs, Wilson, et al., 2009). The task was performed using a hand-held stylus on a 19 inch touch screen (ELO 1928L). The screen displayed five circular targets, a green start button, a red stop button and a central circle (Figure 5.1). Participants were first instructed to move the stylus with the right hand to the start box. After a start signal, they moved the stylus over the screen from the central circle back and forth to the five radial targets and lastly to the stop box. They were instructed to move as accurately and quickly as possible. After performing a block of trials in which the participants actually moved the stylus to the five targets, they were instructed to imagine themselves performing the same movements as accurately and quickly as possible with the eyes open. They again placed the stylus on the start box and then, after the start signal was provided, imagined performing the movements to the targets. After the imagined performance was completed (i.e., when imagining arriving at the stop box), they moved the stylus to the stop box.

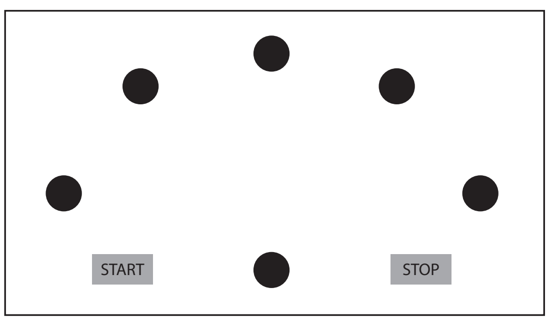

Figure 5.1. Schematic presentation of the radial Fitts' task with target width = 20 mm and target distance = 150 mm. Note that different target distances and widths were used across trials.

In both the actual and imagery task, duration was defined as the time between the start signal and the moment that the stylus reached the stop box. In each trial, the target distance to the central circle and target width was the same for all targets. Target width and target distance to the central circle were varied across trials. Two different target widths and two target distances were combined, resulting in four different task difficulties (i.e., indexes of difficulty; Table 5.3), as computed by *index of difficulty* = log2(2 * *target distance / target width*) (Fitts, 1954). Previous work in adults showed that task order does not affect performance (Papaxanthis et al., 2002). Therefore, participants first performed the actual movement task, followed by the imagery task (see also Hoyek et al., 2009; Spruijt et al., 2013; Williams et al., 2012; Williams et al., 2013). Administering the actual task prior to the imagery task also facilitated children's comprehension of the imagery task. Before the start of the actual movement performance task, participants performed four familiarization trials, whereas before the start of the imagery task, two familiarization trials were provided. The experiment consisted of three repetitions for each index of difficulty, yielding a total of twelve randomly ordered trials in both tasks.

Table 5.3

Indexes of difficulty in the radial Fitts' task

Target distance (mm)	**Target width (mm)**	**Index of Difficulty**
75	20	2.91
150	20	3.91
75	5	4.91
150	5	5.91

<u>Inhibitory control</u>

Inhibitory control was assessed using the validated Go/NoGo task (Rubia et al., 2001). Participants sat in front of a computer screen with the right hand on a button. Colored squares were presented on the screen. The participants were instructed to press the button as quickly as possible when a green square (Go-stimulus) was presented, but to withhold response for a blue square (NoGo-stimulus). In total, 45 Go- and 15 NoGo-stimuli were presented in a random order. The Go-stimuli disappeared immediately after the button press, NoGo-stimuli disappeared after 1500 ms, or when the participant incorrectly pressed the button. During the 1000 to 1500 ms interval between the successive stimuli, a white fixation cross was presented in the center of the screen. Response times and number of errors (i.e., a button press for a NoGo-stimulus) were recorded.

Hand ability tests

As the radial Fitts' task is an upper extremity task, we used two validated hand ability tasks to measure this closely related aspect of motor ability. Gross hand function was assessed with the Box and Block Test (Jongbloed-Pereboom, Nijhuis-van der Sanden, & Steenbergen, 2013; Mathiowetz, Volland, Kashman, & Weber, 1985) and fine hand function with the Purdue Pegboard (Tiffin & Asher, 1948). The Box and Block Test consists of a box divided into two equal parts by a screen. Participants were instructed to move as many blocks as possible to the other compartment of the box, transporting one block at a time, and using one hand only. The outcome measure is the amount of blocks transferred in 60s. The Purdue Pegboard consists of a board with two parallel lines of little holes running vertically down the center of the board. On the top corners, circular compartments contain the pegs. Participants place as many pegs in the holes as possible, one peg at a time, using one hand. The outcome measure is the amount of pegs placed on the board in 30s. Both tasks were performed with the dominant right hand.

Data analyses

For each participant, the average duration was calculated for each index of difficulty, for the actual and imagery performance separately. The temporal congruence between the actual and imagery performance was determined by calculating the Pearson correlation for the individual durations of the two tasks. Individual correlations were then Fisher-Z transformed and subjected to a one-way analysis of variance (ANOVA) to test effects of age on temporal congruence. Age group differences were further analyzed using post-hoc Bonferroni tests. Additionally, we tested for each age group separately whether correlations were significantly larger than 0 with one-sample t-tests.

For the children, a repeated-measures ANOVA was conducted with index of difficulty (2.91, 3.91, 4.91, & 5.91) and task (actual movement & imagery) as repeated factors and age (6, 7, & 8 years) as between-subjects factor. Pairwise comparisons with Bonferroni corrections were used to follow-up on significant findings. When the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied.

Compliance with Fitts' law was analyzed using the goodness of fit (R^2) and slope of the linear regression for the duration and index of difficulty, for each participant separately. Repeated-measures ANOVAs on goodness of fit and slope were used to test whether the linearity of the duration over the different indexes of difficulty differed between task (actual movement & imagery) and age (6, 7 & 8 years). Furthermore, one-sample t-tests were used to test whether the R^2 for the actual and imagery movement performance was larger than 0 for children in each age group separately.

For the adult group, which served as a reference, results were analyzed in a similar manner as the children's results, but without considering age effects (the adult data were not directly compared with the data for the children, because the adults only performed the Fitts' task).

Age differences on the cognitive (response time and number of errors on the Go/NoGo task) and hand ability tests (Purdue Pegboard; Box and Blocks test) were analyzed using separate one-way ANOVAs. Spearman correlations were used to explore the relations between Fitts' task performance and cognitive and hand ability tests for the group of children as a whole and separated by age.

Results

Radial Fitts' task

Mean correlations between the durations of the actual movement and imagery performance are presented in Table 5.4. A significant effect of age ($F(2, 81) = 5.80$, $p < 0.01$, $\eta^2 = 0.128$) indicated that temporal congruence was weaker for the 6-year-olds than for the 8-year-olds. In addition, the correlations were found to be significantly larger than 0, only for the 8-year-olds and the adults (Table 5.4). Individual analyses revealed that three 7-year-olds and five 8-year-olds (10% of all children) had significant ($p < 0.05$) correlations between duration of the actual movement and imagery performance, while thirteen adults (59%) had significant correlations (see Table 5.4). Nonetheless, with the low number of observations for each participant, there is an increased probability of Type 2 errors (e.g., the fairly high correlation among adults (mean $r = 0.854$) might point in that direction). This would result in an underestimation of the number of participants that has significant correlations. To ameliorate, we additionally calculated the number of individual participants showing correlations between duration of actual and imagery performance for α-level of 10% (obviously, the outcomes must be carefully interpreted against the risk for Type 1 errors). This resulted in 16% of the individual children and 77% of the adults showing temporal congruence (i.e., correlations with p-value < 0.1, Table 5.4).

For the children, duration was larger for actual movement performance compared to imagined movement performance ($F(1, 79) = 284$, $p < 0.001$, $\eta^2 = 0.783$). Duration also increased with increasing task difficulty ($F(2.52, 200) = 230$, $p < 0.001$, $\eta^2 = 0.744$). The significant task by difficulty by age interaction ($F(5.29, 209) = 4.09$, $p < 0.001$, $\eta^2 = 0.094$) indicated that duration for the actual pointing performance increased with task difficulty for all age groups, while for the imagery performance increases in movement duration with task difficulty were only found for the 8-year-olds ($F(3, 75) = 5.21$, $p < 0.01$, $\eta^2 = 0.172$; see Figure 5.2). In the group of adults, durations did not differ between actual and imagined movement performance ($p = 0.44$). Duration increased as a function of task difficulty ($F(1.67, 35.1) = 98.7$, $p < 0.001$, $\eta^2 = 0.825$), irrespective of task ($p = 0.421$) (Figure 5.2).

Table 5.4

Results on temporal congruence and linear fit for the different age groups

		6-year-olds (n=28)	**7-year-olds** (n=28)	**8-year-olds** (n=26)	**Adults** (n=22)
Temporal congruence	Correlations (mean *r*)	-0.157	0.189	0.411	0.854
	Correlations > 0	n.s.	n.s.	$t(25) = 3.75$ $p < 0.001$	$t(21) = 13.7$ $p < 0.001$
	n (%) participants with significant positive correlations ($p < 0.05$)	0 (0%)	3 (11%)	5 (19%)	13 (59%)
	n (%) participants with positive correlations ($p < 0.1$)	2 (7%)	5 (18%)	6 (23%)	17 (77%)
Linear fit Actual task	$R^2 > 0$	$t(27) = 49.7$ $p < 0.001$	$t(27) = 34.4$ $p < 0.001$	$t(25) = 84.3$ $p < 0.001$	$t(21) = 67.0$ $p < 0.001$
	n (%) participants with significant R^2 ($p < 0.05$) and slope > 0	13 (46%)	14 (50%)	23 (88%)	18 (82%)
	n (%) participants with R^2 ($p < 0.1$) and slope > 0	20 (71%)	23 (82%)	24 (92%)	21 (95%)
Linear fit Imagery task	$R^2 > 0$	$t(27) = 5.71$ $p < 0.001$	$t(27) = 6.10$ $p < 0.001$	$t(25) = 6.71$ $p < 0.001$	$t(21) = 13.6$ $p < 0.001$
	n (%) participants with significant R^2 ($p < 0.05$) and slope > 0	0 (0%)	4 (14%)	5 (19%)	12 (55%)
	n (%) participants with R^2 ($p < 0.1$) and slope > 0	1 (4%)	6 (21%)	9 (34%)	17 (77%)
Motor imagery ability	*n* (%) participants with significant correlations AND R^2 ($p < 0.05$)	0 (0%)	2 (7%)	4 (15%)	9 (41%)
	n (%) participants with correlations AND R^2 ($p < 0.1$)	1 (4%)	4 (14%)	6 (23%)	15 (68%)

Note: n.s. = not significant; R^2 = goodnes of fit

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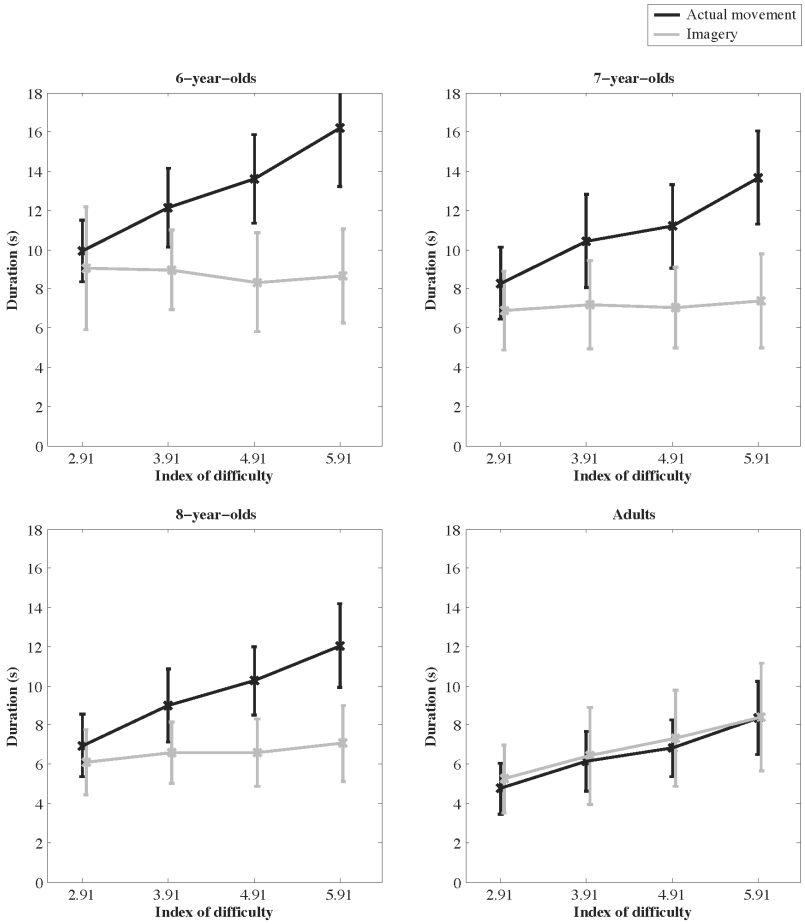

Figure 5.2. Mean durations for the actual and imagery performance as a function of the index of difficulty for the different age groups. Error bars represent the standard deviations of the means.

For the children, the goodness of fit for the linear relation between duration and index of difficulty was higher for the actual movement performance than for the imagery performance ($F(1, 79) = 177$, $p < 0.001$, $\eta^2 = 0.691$). This was evident in all three age groups (Figure 5.3). The slope of this linear function was steeper for the actual motor performance than for the imagery performance ($F(1, 79) = 386$, $p < 0.001$, $\eta^2 = 0.830$). In addition, a significant interaction of task by age was found ($F(2, 79) = 8.35$, $p < 0.001$, $\eta^2 = 0.174$; see Figure 5.3). Post hoc tests indicated that for the actual movement performance, slopes were steeper for the 6-year-olds, compared to the 8-year-olds. For the imagery performance however, slopes were steeper for the 8-year-olds, compared to the 6-year-olds. For the adults, goodness of fit was higher for the actual movement performance ($F(1, 21) = 4.37, p < 0.05, \eta^2 = 0.172$), while the steepness of the slope did not differ between the two tasks (Figure 5.3). Goodness of fit deviated significantly from 0 for participants in all groups, both for the actual and imagined movement performance (Table 5.4). Only 11% of all children had significant linear fits ($p < 0.05$) for the imagined performance, while imagined performance of twelve adults (55%) had significant linear fits (Table 5.4). With an α-level of 10%, compliance with Fitts' law was found for 20% of the children and 77% of the adults (see Table 5.4).

When we combine results for temporal congruence and compliance with Fitts' law, then only 7 to 13% of the children (i.e., for α = 5-10%, respectively; including none or one 6-year-old, two to four 7-year-olds, and four to six 8-year-olds), and 41 to 68% of the adults (nine to fifteen individuals) showed both high temporal congruence and linear goodness of fit (Table 5.4).

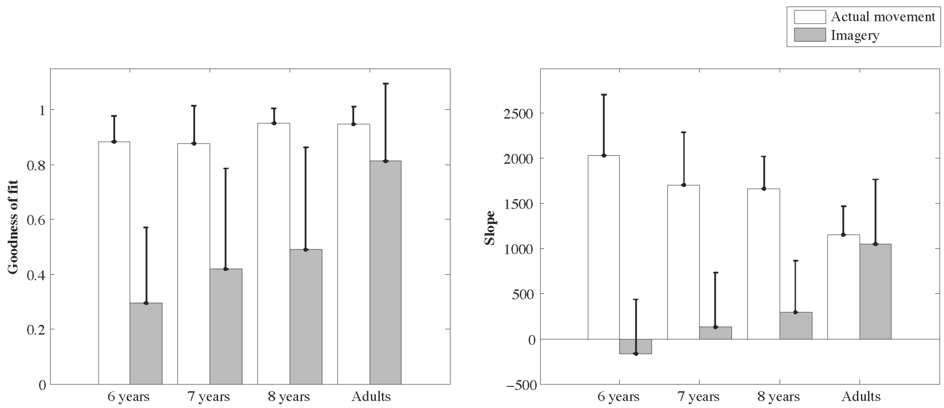

Figure 5.3. Mean goodness of fit *(Left)* and mean slopes *(Right)* for the linear relation between duration and index of difficulty for the actual movement and imagery performance for the different age groups. Error bars represent the standard deviations of the means.

Inhibitory control

Response time significantly decreased with age ($F(2, 81) = 13.2$, $p < 0.001$, $\eta^2 = 0.251$) and the 6-year-old children made more errors in the Go/NoGo task ($F(2, 81) = 7.33$, $p < 0.001$, $\eta^2 = 0.157$) than the 7- and 8-year-old children (Table 5.5).

Hand ability tests

Performance on both the Box and Block Test ($F(2, 81) = 15.3$, $p < 0.001$, $\eta^2 = 0.280$), and on the Purdue Pegboard ($F(2, 81) = 6.88$, $p < 0.01$, $\eta^2 = 0.148$) improved with age (Table 5.5).

Table 5.5

Mean scores on the cognition and hand ability tests, for the three child age groups

	Reaction Time, Go/NoGo (SD)	**n Errors, Go/NoGo (SD)**	**n Pegs, Purdue Pegboard (SD)**	**n blocks, Box and Block Test (SD)**
6-year-olds	685 (170)	2.29 (1.38)	9.43 (1.00)	42.3 (4.90)
7-year-olds	602 (119)	1.18 (1.02)	10.3 (1.63)	46.5 (5.42)
8-year-olds	510 (54.3)	1.27 (1.51)	10.8 (1.37)	49.8 (4.73)

Correlations between motor imagery and cognitive and hand ability tests

For the total group of children it was found that high temporal congruence (i.e., correlation between actual and imagined durations) was significantly, but weakly related to better inhibition (faster responses; r = -0.233, $p < 0.05$), but not to hand ability (Purdue Pegboard or Box and Block Test). Similarly, higher compliance with Fitts' law of the imagined performance (i.e., goodness of fit), was significantly, but weakly related to better inhibition (fewer errors; r = -0.271, $p < 0.05$). Considering the three age groups separately, no significant correlations were found among the measures of motor imagery, cognition and hand ability.

Discussion

We examined the use of motor imagery within the mental chronometry paradigm by means of a radial Fitts' task in 6-, 7-, and 8-year-old children. Previous work on the mental chronometry paradigm in children compared the imagery movement performance in groups of children of different age and suggested that motor imagery ability improves between 5 to 12 years of age (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012). Thus far, however, the use of motor imagery (temporal congruence and compliance with Fitts' law) had not been verified for separate age-groups, resulting in ambiguities with respect to the age at which children are thought to start using motor imagery. Accordingly, we determined to what degree imagery performance in 6-, 7- and 8-year-old children satisfied the two main criteria for motor imagery (i.e., temporal congruence and compliance with Fitts' law) and how this changes with age. The main result was that 6-year-olds were not yet using motor imagery to perform the Fitts' task. The use of motor imagery emerged around 7 years of age. Clearly, however, not all 7- and 8-year-old children were found to engage in motor imagery (see Table 5.4).

In line with previous studies indicating that motor imagery develops during childhood (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012), we found age-related increases for both temporal congruence and compliance with Fitts' law in the imagery task when comparing children of 6, 7 and 8 years of age. In addition, we determined whether performance of the different age groups met these criteria for the use of motor imagery. This indicated that only 8-year-olds (and the adults) showed significant temporal congruence (i.e., correlations between actual and imagined durations were larger than 0) and significant effects of task difficulty on both actual and imagined durations (i.e., the R^2 of the linear regression on imagined durations were larger than 0), consistent with Fitts' law. The results indicate that as a group, 8-year-olds and adults were engaged in motor imagery to perform the mental chronometry task. Because the younger children were not unable to perform the imagery task (i.e., the imagined durations were on the same order of magnitude as the actual durations, even though they did not correlate), they likely used alternative strategies to perform the task. The current study did not use additional tests to identify which alternative non-motor imagery strategies the participants were using, so we can only speculate on these alternative strategies. These might have involved motor memory, visual imagery, or mere counting (Munzert et al., 2009; Sharma et al., 2006). Charting age-related changes in non-motor imagery strategies warrants further study.

The findings with respect to the use of motor imagery ability for the individual children mirrors results on group level (see Table 5.4). That is, at best only one 6-year-old child reliably employed motor imagery (i.e., showed significant temporal congruence and compliance with Fitts' law; $p < 0.1$). However, among the 7-year-olds two to four children were shown to reliably use motor imagery (i.e., 7 to 14%). Among the 8- year-olds, four to six children used motor imagery (i.e., 15 to 23%). The latter is still short of the prevalence among adults, among whom 41 to 68% were reliably engaged in motor imagery to perform the mental chronometry task. Hence, it is to be expected that the proportion of children using motor imagery increases considerably beyond 8 years of age (see Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Choudhury et al., 2007a; Smits-Engelsman & Wilson, 2012). Of the previous studies that examined children's imagery performance within the mental chronometry paradigm, only Smits-Engelsman and Wilson (2012) reported the proportion of children that were found to use motor imagery. Their observations were based on the temporal congruence criterion only. Ten percent of the 5- to 7-year-olds showed a correlation of 0.8 or higher between actual and imagined durations, which compares well with the current 10% of 6- to 8-year-olds with a significant temporal correlation ($p < 0.05$). Smits-Engelsman and Wilson (2012) also reported that among adults, 60% of the individuals showed correlations of 0.8 or higher, while Choudhury et al. (2007a) reported correlations of 0.5 or higher for 75% of the individual adults (the current study observed 59% of the adults with a significant temporal correlation). Nevertheless, these proportions are likely to overestimate the prevalence of the use of motor imagery, because compliance with Fitts' law was not taken into account. Indeed, when taking both criteria into account we found that a lower proportion of participants used motor imagery (7% of the children and 41% of the adults). However, if we accept an increased probability for Type II errors, the proportions become comparable (13% of the children and 68% of the adults). In sum, based on the number of individual children and adults that used motor imagery, we can conclude that the use of motor imagery within the mental chronometry paradigm emerges only at 7 or 8 years of age and not before. Clearly, by age 8 the use of motor imagery, or the proportion of children using motor imagery, has not yet reached adult levels.

The current study extends previous studies by determining the use of motor imagery on an individual level. We showed that even in adults, not all participants used motor imagery on the Fitts' task, indicating that the mental chronometry paradigm does not necessarily enforce the use of motor imagery. These results contrast with previous motor imagery research employing a different paradigm to determine motor imagery ability, in which participants judged laterality of depicted hands. These studies generally found that adults were able to use motor imagery (Parsons, 1994; ter Horst et al., 2010) and even a large portion of 5-year-olds was already using motor imagery (Funk et al., 2005; Krüger & Krist, 2009). The discrepancy between the use of motor imagery for judging hand laterality and the mental chronometry task suggests that motor imagery performance is dependent on the task. The mental chronometry paradigm seems to be a conservative measure that may underestimate the ability to use motor imagery. To conclude, we recommend studying motor imagery via multiple paradigms or tasks to be able to draw more general conclusions on the ability of participants to use motor imagery.

Finally, we also explored the relation of hand and cognitive abilities with the ability to enlist motor imagery. In line with a previous study showing that motor imagery ability was not related to hand ability in children younger than 11 years (Caeyenberghs, Tsoupas, et al., 2009), we also did not find a relation between motor imagery ability and hand ability. Our results indicate that motor imagery ability was, however, related to inhibition. Motor imagery performance was found to be only weakly related to inhibition for the total group of children, not for the separate age groups. This might be explained by the low number of 6- to 8-year-old participants who actually used motor imagery. Summing up, our results provide some suggestions that children's ability to enlist motor imagery may be related to inhibitory processes. A challenge remains for future studies to further examine whether and how inhibitory processes mediate the relation between age and motor imagery. To elucidate developmental constraints on the ability to engage in motor imagery, studies that scrutinize other cognitive processes as well are warranted. For example, working memory has been suggested to be related to the ability to use motor imagery (Choudhury et al., 2007a; Gabbard et al., 2013; Malouin et al., 2004).

In conclusion, the current study suggests that the use of motor imagery in the mental chronometry paradigm emerges at 7 or 8 years of age. Younger children did not show evidence of using motor imagery. However, the current study also indicates that the mental chronometry paradigm using the Fitts' task might be a conservative measure of motor imagery. Therefore, the Fitts' task can best be implemented in combination with motor imagery tasks from a different paradigm to obtain insight into the development of motor imagery in children.


6

Motor imagery ability for walking in 6- to 9-year-old children

Manuscript submitted – Under review

Abstract

Previous mental chronometry studies indicated that children's motor imagery only emerges between 7 and 8 years of age with further developments up to age 12. Typically, these studies involved goal-directed pointing tasks. The aim of the present study was to examine the generality of these observations by examining children's motor imagery on a walking task. To this end, we assessed durations of actual walking and imagined walking as a function of task difficulty (i.e., path length and width) in 83 children of 6 to 9 years old. We found significant temporal congruence and adherence to Fitts' law, even among the 6-year-olds. Hence, motor imagery ability for walking appeared to emerge at younger age than for pointing. We argue that motor imagery performance depends on the familiarity with the motor task and discuss implications for research and pediatric rehabilitation.

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When people imagine performing a movement, similar neural networks are activated as during the actual execution of movements (Decety & Grezes, 1999). Studying motor imagery can provide insight into cognitive aspects of motor control, because execution and imagery of movements involve the same motor representations (Jeannerod, 1994). As such, obtaining insight into changes in children's motor representations across development can facilitate our understanding of mechanisms that are involved in motor development. The mental chronometry paradigm is frequently used to determine motor imagery ability in children (for a review, see Spruijt, van der Kamp, et al., 2015b). Using this paradigm, participants not only actually perform a motor task, but also imagine performing the very same task without actually moving. Owing to the shared motor representations between motor execution and motor imagery, actually performed and imagined movements typically adhere to the same motor constraints (Munzert et al., 2009). Consequently, the mental chronometry task involves motor imagery if a strong association is observed between the actual and imagined performance.

The most commonly used task in mental chronometry is goal-directed pointing to targets (e.g., Caeyenberghs, van Roon, et al., 2009; Maruff et al., 1999; Williams et al., 2013). In adults, high congruence between the duration of actual and imagined pointing movements was shown, which may be indicative of the use of motor imagery (Cerritelli et al., 2000; Choudhury et al., 2007a; Sirigu et al., 1996). Nonetheless, this observed temporal congruence can also be explained by strategies that are not grounded in motor processes, such as counting or making an estimated guess by means of former experiences with the movement (Munzert et al., 2009). By ascertaining that both actual and imagined movements are similarly affected by task constraints (e.g. task difficulty), the goal-directed pointing task allows the researcher to determine whether or not the employed imagery strategy is actually embedded in motor processes (Currie & Ravenscroft, 1997). That is, in adults, a lawful relation between the duration of actual pointing movements and task difficulty exists that can be expressed as movement duration = a + b * index of difficulty; with index of difficulty = log2 (2 * target distance / target width); (Fitts' law; Fitts, 1954). Importantly, Fitts' law was also observed for imagined movements (Cerritelli et al., 2000; Choudhury et al., 2007a; Sirigu et al., 1996). Thus, the presence of temporal congruence between actual and imagined movements and adherence to Fitts' law together indicate the use of motor imagery strategies for imagining goal-directed pointing movements in adults.

Alongside considerable developmental changes in motor ability during childhood, previous studies have indicated substantial improvements in motor imagery ability in children between 5 and 12 years of age (Spruijt, van der Kamp, et al., 2015b). This is evidenced by increased temporal congruence between actual and imagined performance with age and age-related increases in the impact of task difficulty on the imagined performance of goal-directed pointing movements (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012). In line with this, we recently showed that the use of motor imagery during the pointing task emerges around the age of 7 or 8, with increased involvement thereafter (Spruijt, van der Kamp, et al., 2015a).

The present study is aimed at examining the generality of children's developmental differences in motor imagery. Specifically, it was previously suggested that motor imagery performance is dependent on the specific motor task under study (Caeyenberghs, Tsoupas, et al., 2009; Crognier et al., 2013; Fusco et al., 2014; Kunz et al., 2009) and in particular the individual's familiarity with the motor task (Bohan et al., 1999; Kalicinski & Raab, 2014; Spruijt et al., 2013). That is, as mental representations for particular movements are built up and updated as a result of motor actions and experiences (Wolpert, 1997), it can be expected that individuals have better motor imagery capability for familiar movements compared to movements with which they have less experience and thus are less familiar with. In line with this hypothesis it was recently shown that movement experience is associated with motor imagery in adults: motor imagery performance was observed to be superior for forward walking compared to lateral walking (Fusco et al., 2014).

Based on the above lines of reasoning combined with the observation that most studies targeting children's motor imagery ability have employed relatively artificial upper limb pointing tasks, we examined the extent to which previous developmental differences in motor imagery on the pointing task generalize to a walking task. To this end, we determined the age at which children start to display motor imagery on a goal-directed walking task and examined its development between 6 and 9 years of age. Previous studies in adults and children with cerebral palsy have shown that an experimental protocol that comprises walking tasks of varying difficulties indeed allows for studying motor imagery of gait (Bakker et al., 2007; Spruijt et al., 2013; Stevens, 2005). In these studies, task difficulty was found to influence actual and imagined walking performance in a similar way. Possibly, children are more familiar with the current walking task than with the experimental goal-directed pointing task used in previous work. Accordingly, we hypothesized that evidence for the use of motor imagery in the walking task should be stronger at 6, 7, and 8 years of age than was previously established for the pointing task (Spruijt, van der Kamp, et al., 2015a).

Methods

Participants

Typically developing children were recruited from mainstream primary schools. The 83 right-hand children were divided in four age groups of 6, 7, 8, and 9 years (see Table 6.1). Children's parents provided written informed consent prior to the experiment. The local ethics committee approved the study before participant recruitment.

Table 6.1

Characteristics of the participant groups

Age group	Mean age (SD) in years	Gender (% male)
6-year-olds (n=18)	6.61 (0.16)	38.9%
7-year-olds (n=21)	7.43 (0.28)	57.1%
8-year-olds (n=26)	8.58 (0.29)	42.3%
9-year-olds (n=18)	9.40 (0.29)	33.3%
Total group (n=83)	8.04 (1.05)	43.4%

Material and Procedure

Motor imagery was assessed by means of actual walking and imagining walking along different straight paths, which were marked on the ground surface with two taped lines (Figure 6.1). In the walking task, a button was placed on a chair at the end of the path. In the imagery task, a button was placed on a chair at the start of the path. The buttons were placed at the child's right-hand side. In the actual walking task, participants stood behind the start line and were instructed to start walking between the lines after the start signal (a beep) was presented. The participants pressed the button at the end of the path after they crossed the finish line. The participants were instructed to walk at their own regular pace without stepping on the lines and were told not to run. In the imagery task, participants stood behind the start line and were instructed to imagine that they were walking between the lines at their own regular pace with the eyes open, but without actually moving. They were told to start the imagined walking at the sound of the start signal, and to press the button when they imagined they had crossed the finish line.

Path width and path length were varied across the trials, yielding four paths with different task difficulty (Table 6.2; index of difficulty = log2 (2 * *path length* / *path width*)) (Fitts, 1954). Participants first performed a block of actual walking trials, after which they performed a block of imagined walking trials, in order to facilitate children's understanding of the imagery task (see also Spruijt, van der Kamp, et al., 2015a). It was previously shown in adults that task order does not affect performance (Papaxanthis et al., 2002). Each of the four paths was performed three times, resulting in twelve randomly ordered trials per task. The two short paths (see Table 6.2) were performed before the start of both the walking task and the imagery task, to familiarize the participants with the tasks.

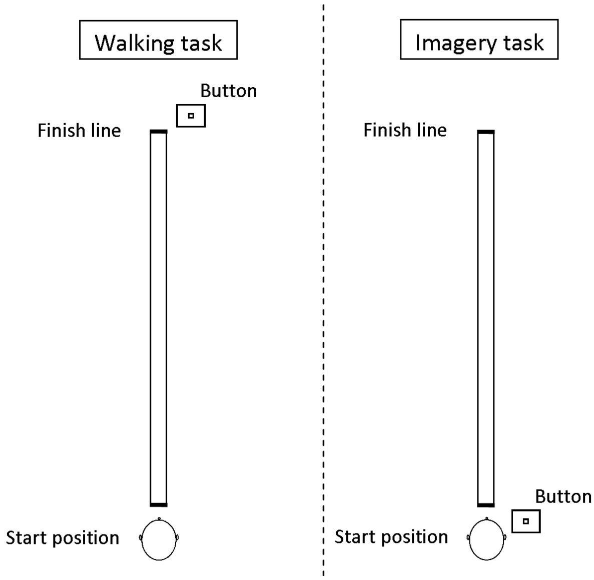

Figure 6.1. Experimental set-up for the walking and imagery task.

Table 6.2

Indexes of difficulty in the walking task

Path length (cm)	**Path width (cm)**	**Index of Difficulty**
200	20	4.32
200	10	5.32
600	20	5.91
600	10	6.91

Data analyses

Durations of actual and imagined walking, which were defined as the time between the presentation of the start signal and the button press, served as the main dependent measures. The individual durations were averaged per index of difficulty, for each task separately. Pearson correlation between the actual and imagery duration was calculated, and the Fisher-Z transformed individual correlations were subsequently submitted to a one-way analysis of variance (ANOVA) to test the effects of age on temporal congruence. Further analyses of age group differences were performed using post-hoc Bonferroni tests. We used one-sample t-tests to test whether the mean correlations were significantly larger than 0 per age group.

In addition, the individual mean durations per index of difficulty were submitted to repeated-measures ANOVA, with index of difficulty (4.32, 5.32, 5.91, 6.91) and task (walking & imagery) as within-subject factors and age (6, 7, 8, 9 years) as the between-subjects factor. Significant main effects were followed up with post-hoc Bonferroni tests and significant interaction effects were followed up with an additional ANOVA Violations of the assumption of sphericity were corrected by means of a Greenhouse-Geisser correction.

Furthermore, a linear regression analysis was performed on the individual mean durations across the four indexes of difficulty. Repeated-measures ANOVAs on individual goodness of fit and slope were used to test whether the linearity of the duration across the indexes of difficulty differed between the tasks (walking & imagery) and across age (6, 7, 8, 9 years). Furthermore, we tested whether the goodness of fit for the walking and imagery was larger than 0 by means of one-sample t-tests for each age group separately.

Finally, the proportion of the children that was using motor imagery to perform the imagined walking task was determined per age group. As introduced in our recent mental chronometry study (Spruijt, van der Kamp, et al., 2015a), the use of motor imagery was defined by the individual child demonstrating both significant temporal congruence between actual and imagined walking, and significant adherence to Fitts' law for the imagined performance.

Results

Table 6.3 shows the mean correlations between actual and imagined walking durations. The correlations were significantly larger than 0 in all age groups. Yet, age was shown to significantly affect the temporal congruence ($F(3,82) = 3.286$; $p = 0.025$; $\eta^2 = 0.111$). Post hoc analyses indicated higher correlations in 9-year-olds compared to 6-year-olds. Individual analyses furthermore showed that the percentage of children with significant correlations ($p < 0.05$) between actual and imagined walking durations increased from 17% among the 6-year-olds to 72% among the 9-year-olds (see Table 6.3). However, it must be taken into account that due to the low number of observations per participant, the probability of Type 2 errors is relatively high, which may result in an underestimation of the number of participants that show a significant correlation between the two tasks. Therefore, Table 6.3 also reports the percentage of participants showing significant correlations for α-level of 10% (see also Spruijt, van der Kamp, et al., 2015a). This resulted in 33% of the 6-year-old children and up to 94% of the 9-year-old children showing temporal congruence.

Table 6.3

Results on temporal congruence and linear fit for the different age groups

		6-year-olds (n=18)	**7-year-olds** (n=21)	**8-year-olds** (n=26)	**9-year-olds** (n=18)
Temporal congruence	Correlations (mean *r*)	0.851	0.909	0.928	0.958
	Correlations > 0	$t(17) = 33.0$ $p < 0.001$	$t(20) = 50.2$ $p < 0.001$	$t(25) = 65.3$ $p < 0.001$	$t(17) = 83.9$ $p < 0.001$
	n (%) participants with significant positive correlations ($p < 0.05$)	3 (17%)	7 (33%)	14 (54%)	13 (72%)
	n (%) participants with positive correlations ($p < 0.1$)	6 (33%)	14 (67%)	20 (77%)	17 (94%)
Linear fit Actual task	$R^2 > 0$	$t(17) = 63.4$ $p < 0.001$	$t(20) = 84.2$ $p < 0.001$	$t(25) = 68.4$ $p < 0.001$	$t(17) = 58.9$ $p < 0.001$
	n (%) participants with significant R^2 ($p < 0.05$) and slope > 0	10 (56%)	16 (76%)	14 (53%)	8 (44%)
	n (%) participants with R^2 ($p < 0.1$) and slope > 0	17 (94%)	20 (95%)	24 (92%)	16 (89%)
Linear fit Imagery task	$R^2 > 0$	$t(17) = 19.2$ $p < 0.001$	$t(20) = 44.0$ $p < 0.001$	$t(25) = 50.6$ $p < 0.001$	$t(17) = 48.9$ $p < 0.001$
	n (%) participants with significant R^2 ($p < 0.05$) and slope > 0	3 (17%)	8 (38%)	14 (53%)	9 (50%)
	n (%) participants with R^2 ($p < 0.1$) and slope > 0	9 (50%)	16 (76%)	18 (69%)	15 (83%)
Motor imagery ability	*n* (%) participants with significant correlations AND R^2 ($p < 0.05$)	1 (6%)	3 (14%)	9 (35%)	6 (33%)
	n (%) participants with correlations AND R^2 ($p < 0.1$)	6 (33%)	13 (62%)	14 (54%)	14 (78%)

Note: R^2 = goodnes of fit

Figure 6.2 presents the actual and imagined walking durations as a function of task difficulty for all age groups. Durations were larger with increasing task difficulty ($F(1.55, 122) = 315$, $p < 0.001$, $\eta^2 = 0.800$), and larger for imagined walking compared to actual walking ($F(1, 79) = 52.5$, $p < 0.001$, $\eta^2 = 0.399$). In addition, task significantly interacted with difficulty and age ($F(5.85, 154) = 3.17$, $p < 0.01$, $\eta^2 = 0.107$). Follow-up analyses showed that task only interacted with difficulty in the 6-year-olds ($F(3, 51) = 7.03$, $p < 0.001$, $\eta^2 = 0.293$) and 8-year-olds ($F(3, 75) = 3.26$, $p < 0.05$, $\eta^2 = 0.115$), but not in the 7- and 9-year-olds. Although difficulty thus affected the actual walking durations differently than the imagined walking durations in 6- and 8-year-olds (see Figure 6.2), additional analyses showed that both actual and imagined walking durations significantly increased as a function of task difficulty.

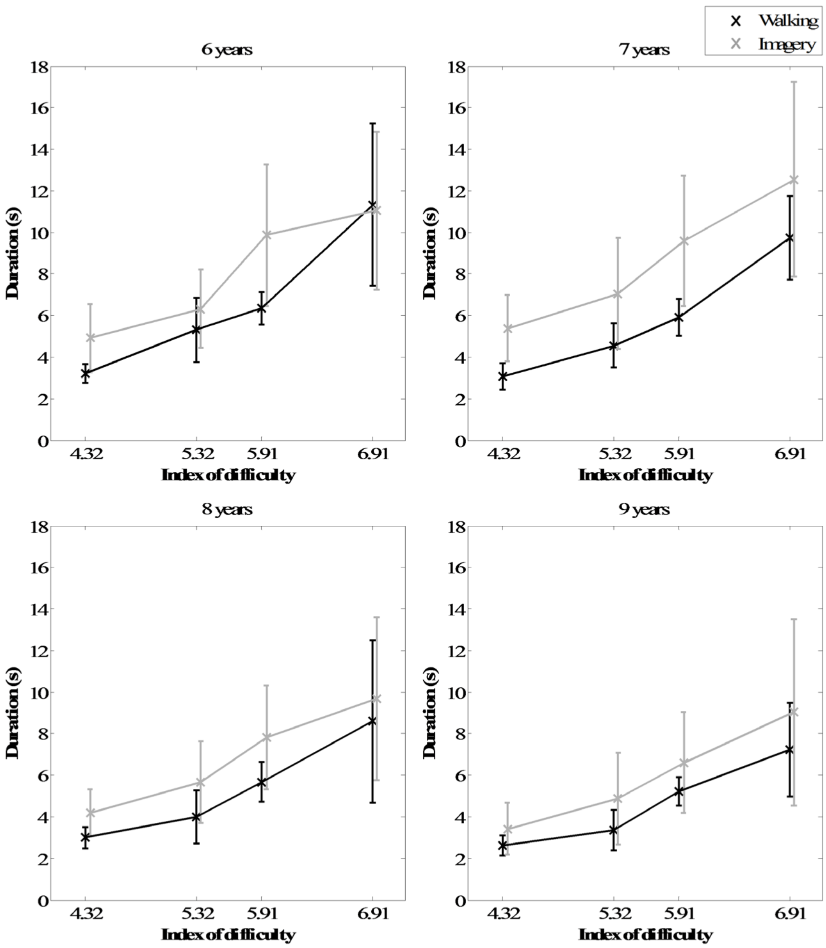

Figure 6.2. Averaged walking and imagery duration as a function of task difficulty. Error bars represent the standard deviation of the mean.

The slope of the linear function between duration and task difficulty did not differ between actual and imagined walking (p = 0.831). However, the goodness of fit for actual walking was higher than for imagined walking ($F(1, 79) = 12.0$, $p < 0.001$, η^2 = 0.132) and a significant task by age interaction was found for the goodness of fit ($F(3, 79) = 4.42$, $p < 0.01$, η^2 = 0.144). Follow-up analyses showed that the goodness of fit for imagined walking increased with age ($F(3, 79) = 3.84$, $p < 0.05$, η^2 = 0.127), but the goodness of fit for actual walking did not differ across age (see Figure 6.3). Goodness of fit was higher than 0 in all groups, both for the actual and imagined walking (Table 6.3). A significant linear relation between imagined walking duration and task difficulty was only found among 17% of the 6-year-old children, whereas half of the 8- and 9-year-old children significantly adhered to Fitts' law (with p < 0.05). With an α-level of 10%, adherence to Fitts' law was found to range from 50% in 6-year-olds to 83% in 9-year-olds (see Table 6.3).

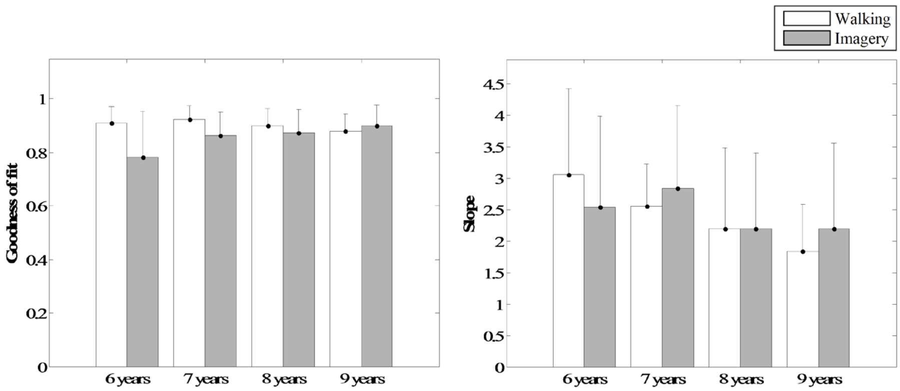

Figure 6.3. Mean goodness of fit *(Left)* and mean slope *(Right)* for the linear relations between duration and task difficulty for the walking and imagery performance. Error bars represent the standard deviation of the mean.

When combining the results for temporal congruence and adherence to Fitts' law, only one 6-year-old child (6%) showed both high temporal congruence and linear goodness of fit for α = 5%. 14% of 7-year-olds and up to a third of the 8- and 9-year-old children showed motor imagery ability. For α = 10%, these percentages amount to 33% of the 6-year-olds and 78% of the 9-year-olds (Table 6.3).

Discussion

The present study examined whether the previously observed developmental differences in motor imagery in pointing tasks generalize to a walking task. Previous studies using mental chronometry of goal-directed pointing indicated that from 7 to

8 years onwards, motor imagery ability improves with age (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012; Spruijt, van der Kamp, et al., 2015a). For example, in a previous pointing task study adopting the same methods of analysis, we observed that among 6-year-olds, 0 to 4% of children employed a motor imagery strategy, while 7 to 14% of 7-year-olds and 15 to 23% of 8-year-olds were observed to use motor imagery (Spruijt, van der Kamp, et al., 2015a). In the current walking experiment, these percentages were 6 to 33% for 6-year-olds, 14 to 62% for 7-year-olds and 35 to 54% for 8-year-olds, respectively. In brief, the present results demonstrated that children's imagery performance on the walking task was affected by motor constraints (i.e., task difficulty) already at 6 years of age, at least in a minority of children. The influences of motor constraints on imagery performance increased across age. This indicates that motor imagery develops earlier in walking than for pointing. We will now elaborate on the present walking results and the comparison with previous studies on goal-directed pointing.

The current study shows that on a group level children's imagery performance was influenced by motor constraints from 6 to 9 years of age. This was evidenced by high temporal congruence between actual and imagined walking, with correlations ranging between 0.851 and 0.958 (see Table 6.3). Furthermore, in all age groups both the actual walking and imagined walking performance adhered to Fitts' law. The group findings that motor imagery is already used from 6 years onwards are in line with our observations in individual children, as a small proportion of 6-year-olds (i.e., estimated between 6 and 33%) already displayed an ability to use motor imagery in the imagined walking task (see Table 6.3).

The finding that motor imagery increases with age (combined increasing temporal congruence and adherence to Fitts' law for the imagined walking) are in line with previous mental chronometry studies that showed developmental differences in motor imagery ability (e.g., Caeyenberghs, Wilson, et al., 2009; Molina et al., 2008). Age-related increases in motor imagery ability were also evident from the proportion of children that displayed motor imagery ability. Taken together, it can be concluded that a proportion of children is already engaged in motor imagery for walking at 6 years of age and motor imagery use increases onwards, at least up to age 9.

Our results on the walking task are distinct from previous results on goal-directed pointing in children. First, temporal congruence is considerably higher for walking (e.g., 0.851 at 6 years of age and 0.928 at 8 years of age) than for goal-directed pointing (e.g., -0.157 at 6 years of age and 0.411 at 8 years of age) (Spruijt, van der Kamp, et al., 2015a) (see also Caeyenberghs, Tsoupas, et al., 2009; Smits-Engelsman & Wilson, 2012). Second, imagined walking significantly adhered to Fitts' law in 6- to 9-year-olds (see Figure, 2), whereas previous studies indicated that imagined pointing durations did not, or only marginally increase with task difficulty in 5- to 8-year-old children (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012; Spruijt, van der Kamp, et al., 2015a). Third, in contrast to the observation that at least a proportion of 6-year-old children already use motor imagery on the walking task, motor imagery only emerged between 7 or 8 years of age for imagined pointing (Spruijt, van der Kamp, et al., 2015a). These differences between motor imagery for walking and motor imagery for pointing are in line with suggestions that motor imagery performance depends on the motor task that is used (Caeyenberghs, Tsoupas, et al., 2009; Crognier et al., 2013; Fusco et al., 2014; Kunz et al., 2009). We propose that the difference between our results and those for pointing might be explained by familiarity with the task. Specifically, motor experience is a key factor for building and updating motor representations (Wolpert, 1997). These motor representations are not only thought to support actual motor execution, but also to be involved in motor imagery (Jeannerod, 2001). Indeed, we found that motor imagery performance was better for a familiar task with which children have ample experience such as walking, compared to consecutive pointing, which is a more artificial and less familiar task. It must be acknowledged, however, that we compared motor imagery performance between two groups of children. Even though we administered identical methods to determine motor imagery ability in typically developing children, we did not perform a direct comparison of motor imagery performance within a group of children.

A dependence of motor imagery performance on the familiarity with the task has implications for the use of motor imagery training in the rehabilitation context (for a review, see Malouin & Richards, 2010). Accumulating evidence suggests that motor imagery training improves motor performance after stroke, by stimulating the same neural networks that are involved in controlling movements (e.g., Sharma et al., 2006; Zimmermann-Schlatter et al., 2008). Motor imagery training was also suggested as a rehabilitation tool for children with developmental motor disorders, such as cerebral palsy and developmental coordination disorder (Steenbergen et al., 2009). Familiarity with the motor task may be particularly critical for children with developmental motor disorders, in order to benefit from motor imagery. In contrast with stroke patients who have had extensive movement experiences prior to their insult, this is not the case for children with developmental motor disorders, as they are born with a compromised ability to perform a multitude of movement tasks and therefore might not have extensive movement experiences. For example, walking performance might not benefit from motor imagery training in children who have never experienced walking as a result of early brain damage (see also Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004). In contrast, when rehabilitation programs target movements that are compromised in children with motor disorders, but with which they have ample experience, motor imagery training can be a valuable addition to physical practice for pediatric rehabilitation (see Wilson et al., 2002).

In conclusion, the current study suggests that motor imagery performance may not fully generalize across motor tasks, as evidenced by an earlier emergence of motor imagery and stronger evidence that 6- to 9-year-olds used motor imagery on the walking task, than on the pointing task. This distinction may be attributed to the familiarity with the motor task. Capturing the ability to engage in motor imagery can therefore best be examined by means of a motor imagery paradigm comprising a familiar motor task for the participants. Finally, we recommend motor imagery training protocols to implement motor tasks that are as familiar as possible.


7

Assessment of motor imagery in cerebral palsy via mental chronometry: The case of walking

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Abstract

Recent studies show varying results on whether motor imagery capacity is compromised in individuals with cerebral palsy (CP). Motor imagery studies in children predominantly used the implicit hand laterality task. In this task participants judge the laterality of displayed hand stimuli. A more explicit way of studying motor imagery is mental chronometry. This paradigm is based on the comparison between the movement durations of actually performing a task and imagining the same task. The current study explored motor imagery capacity in CP by means of mental chronometry of a whole body task. Movement durations of 20 individuals with CP (mean age = 13 years, SD = 3.6) were recorded in two conditions: actual walking and imagined walking. Six unique trajectories were used that varied in difficulty via manipulation of walking distance and path width. We found no main effect of condition (actual walking versus imagining) on movement durations. Difficulty of the walking trajectory did affect movement durations. In general, this was expressed by an increase in movement durations with increasing difficulty of the task. No interaction between task difficulty and movement condition was found. Our results show that task difficulty has similar effects on movement durations for both actual walking and imagined walking. These results exemplify that the tested individuals were able to use motor imagery in an explicit task involving walking. Previous studies using the implicit hand laterality task showed varying results on motor imagery capacity in CP. We therefore conclude that motor imagery capacity is task dependent and that an explicit paradigm as the one used in this study may reveal the true motor imagery capacity. The implications of these findings for the use of motor imagery training are discussed.

Individuals with cerebral palsy (CP) have compromised motor behaviour, due to congenital disturbances in the brain (Bax, Goldstein, Rosenbaum, Leviton, & Paneth, 2005). One facet of this compromised motor behaviour is an impaired motor planning ability which is proposed to be related to an impaired ability to use motor imagery (e.g., Mutsaarts, Steenbergen, & Bekkering, 2006). Motor imagery is the mental simulation of a motor act, without any overt motor execution (Decety, 1996a). Motor imagery is related to motor representations that are involved in planning and controlling movements. According to Jeannerod (1994), these motor representations may be regarded as the conscious experience of internal models of intended motor actions. As such, they have a distinctive role in the feed-forward planning and control of movements.

In addition to studies reporting that motor planning is affected in individuals with CP (Crajé, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010), lines of empirical evidence suggest that the capacity to use motor imagery may be impaired in CP (Crajé, van Elk, et al., 2010). Thus far, motor imagery capacity in adolescents with CP was generally studied by means of a hand laterality task. In this task, a judgment on the laterality of a displayed hand stimulus has to be made as quickly as possible via a button press. The task was designed to elicit implicit motor imagery. That is, in order to judge the laterality of the hand stimulus, participants have to imagine rotating their own hands. In the hand laterality task, the response duration profiles are the main outcome measures to reflect motor imagery capacity. The use of motor imagery is indicated when characteristics that affect actual movements, similarly affect the imagined task. For instance, in studies with adults and typically developing children it was shown that the response durations increased with an increasing rotation angle away from the canonical orientation of the presented hand stimulus (e.g., Funk et al., 2005; Parsons, 1994). In addition, response durations to hand stimuli in orientations that are biomechanically more demanding were longer, compared to those in less demanding orientations. To exemplify, medially oriented hand stimuli are biomechanically easier to perform and judgment of these hands resulted in shorter response durations, compared to judging laterally oriented hand stimuli (e.g., Caeyenberghs, Tsoupas, et al., 2009). The combined behavioural effects of rotation angle and biomechanical constraints of the hand stimuli on the response duration profiles are crucial to draw conclusions on motor imagery ability (ter Horst et al., 2010).

The results on the hand laterality task to study motor imagery capabilities in individuals with CP are equivocal. In two studies, the effect of rotation angle on response durations was considered (Mutsaarts et al., 2007; Steenbergen et al., 2007). In the study of Mutsaarts et al. (2007) it was shown that the group of individuals with hemiplegia on the left body side displayed the expected effect of longer response durations for hand stimuli with larger rotation angles, but this effect was not found for the group with right-sided hemiplegia. In contrast, Steenbergen et al. (2007) reported an overall effect of rotation angle on response durations for both left- and right-side affected CP. Next to the effect of rotation angle on the response duration profile, other studies also examined the effect of biomechanical constraints on response durations in CP. These studies also showed equivocal results. In one study, adolescents with right-sided hemiplegic CP did not show an effect of medially versus laterally oriented hand stimuli (Crajé, van Elk, et al., 2010), while other studies did observe an effect of biomechanically constraining orientations on response durations in children with both left- and right-side affected CP (Williams, Anderson, et al., 2011; Williams, Reid, et al., 2011). Collectively, these studies do not allow a definite conclusion as to whether motor imagery capacity is compromised in CP.

An essential feature of the hand laterality task is that it, in principle, implicitly elicits motor imagery. We argue that this task may therefore not be most suitable to assess motor imagery capacity in individuals with CP. It is known that these individuals have impaired sensorimotor integration (Gordon, Charles, & Steenbergen, 2006), which may lead to a decreased body awareness. In motor imagery, however, body awareness is critical as the individual produces a kinesthetic image of the motor action. It may be suggested that an explicit way of assessing motor imagery capacity, as is the case in mental chronometry tasks, may facilitate body awareness and consequently motor imagery. Indirect evidence for this suggestion stems from research using the hand laterality task. Sirigu and Duhamel (2001) showed that explicit instruction facilitates the use of motor imagery in this task. Specifically, participants were instructed to rotate the hand from a 'first-person' perspective (motor imagery), or from a 'third-person' perspective (alternative imagery strategy). During the task, participants placed their hand on the lap or behind the back. Sirigu and Duhamel found that posture had an effect on response times only when participants were instructed to rotate the hand from a 'first-person' perspective. Importantly, these results suggest that participants were able to use motor imagery, but this capacity was 'hidden' when no explicit motor imagery instructions were provided in the hand laterality task.

In the mental chronometry task, the instruction to perform the movement from a first person perspective forms an essential element of the experimental paradigm. Therefore, this task may be better suited to assess true motor imagery capacity in individuals with CP (see Williams et al., 2012). In a study using this paradigm in typically developing children, Caeyenberghs, Wilson, van Roon, Swinnen, and Smits-Engelsman (2009) considered temporal congruence between an actual motor task and imagining this motor task and the effect of task difficulty (as manipulated via Fitts' law, 1954) on movement durations. Movement durations for both conditions were congruent. Furthermore, task difficulty not only affected movement durations of the actual performance, but similarly influenced imagined movement durations. As the combination of these results indicated that imagery of the motor task was similarly affected by task constraints as the actual motor task, this led to the conclusion that the children in this study were able to use a motor imagery strategy to perform the task.

Thus far, the mental chronometry paradigm was used only once to study motor imagery capacity in CP. Williams et al. (2012) reported that the movement durations of performed and imagined finger pointing movements were in line with Fitts' law in both a control group and in a group of children with right-sided hemiplegic CP. For children with an affected left body side however, only actual performance was in line with Fitts' Law. No lawful relationship between movement durations and task difficulty was found in the imagery condition. This indicates that these children did not use a motor imagery strategy to perform the imagery task. Note that Williams et al. (2012) reported an affected motor imagery capacity in left-sided hemiplegics (i.e., primarily right hemisphere damage), which is in contrast with earlier reported findings on the hand laterality task that motor imagery capacity is compromised in right-sided hemiplegics (Mutsaarts et al., 2007). According to Williams et al. these differences might be explained by the level of motor function of the participants. As the group of children with right-sided hemiplegia had better levels of motor function, compared to the included children with left-sided hemiplegia, the group difference in motor imagery performance might be attributed to function level, instead of affected side.

Collectively, it is presently not clear whether participants with CP are indeed affected in their capacity to use motor imagery. We argue that the implicit nature of the hand laterality task may conceal the true motor imagery capacity in CP. Using a mental chronometry task, the present study assesses motor imagery in a more explicit manner. Furthermore, we use walking as experimental motor task, because this task is familiar and well practiced, compared to more artificial hand rotations. With this, we increase the ecological validity of the task, and the semantics of the context. In a similar vein, it was shown that adolescents with CP reveal more appropriate motor planning in a context that resembles an everyday life task (turning over a glass and pour water in it) compared to a more artificial experimental motor planning task (turning over a bar; Steenbergen, Meulenbroek, & Rosenbaum, 2004). Similar to previous studies using the mental chronometry paradigm in adults and children (e.g., Caeyenberghs, Tsoupas, et al., 2009; Decety et al., 1989) we manipulated task difficulty via variation of the index of difficulty (ID, determined by the combination of path length and path width). The previous studies showed a speed-accuracy trade-off (Fitts, 1954) in both imagined and exectued conditions, evidencing the use of motor imagery. In the present study we systematically manipulated the ID, under the assumption that motor imagery is used when movement durations in both conditions are similarly constrained by task difficulty. Furthermore, by using a range of IDs instead of only one combination of path length and path width, we obviate the use of alternative strategies in the imagery condition, such as counting.

Methods

Participants

A total of 20 participants (16 male, mean age = 13, SD age = 3.55) diagnosed with CP were included in the study. The participants were recruited at two schools for special education in the Netherlands. Inclusion criteria to participate in the study were: 1) diagnosed with CP; 2) able to walk a distance of 5 meters. Informed consent was obtained from the parents. Of the participants, 5 were diagnosed with left-sided hemiplegic CP, 8 with right-sided hemiplegic CP, 5 participants were bilaterally affected and for 2 participants there was no known diagnosis which side of the body was primarily affected. All participants walked without assistive mobility devices, so they had a level 1 or 2 score on the GFMSC. IQ scores were available from the individual medical records, except for two participants. Mean IQ scores (Wechsler Intelligence Scale for Children – Revised) were 76.6, SD = 13.6. The level of motor functioning was assessed by means of the scores on the Box and Blocks test (Mathiowetz et al., 1985). This test for manual dexterity was performed with the preferred hand (mean = 47.8, SD = 11.3) and the non-preferred hand (mean = 30.6, SD = 17.9).

Material and procedure

Motor imagery was measured by means of a mental chronometry paradigm involving walking, similar to the task described by Bakker, de Lange, Stevens, Toni and Bloem (2007). The walking trajectories were shown by lines on the floor. At the start, a line on the floor marked the beginning of the trajectory. The end of the trajectory was marked by a green finish square the participants had to step on. In the actual performance condition, a button was placed on a table next to the finish, at the side of the least affected hand of the participant, while the button was placed at the beginning of the trajectory during the imagery condition.

Participants were first instructed to walk the trajectory at a comfortable pace. After a start signal was presented, they walked the trajectory, placing their feet within the lines. They pressed the button with the less affected hand when they arrived at the green square. Furthermore, participants were instructed to imagine themselves performing the same movement trajectory, while standing at the start position. They began imagining following the start signal and pressed the button when the imagined movement was completed, that is when they imaged that they arrived at the green square. Participants were instructed to imagine the movement from a first person perspective with their eyes open. In both conditions, movement duration was recorded as the time between the start signal and the button press. Six trajectories were used that differed in ID via variation of the width and length of the trajectory (Table 7.1). Each unique trajectory was performed three times, yielding a total of eighteen randomly ordered trials in both movement conditions for each participant. All participants first performed the executed walking condition, followed by the imagined walking condition.

Data analyses

In two participants the movement duration of one trial was removed from the data, as these were regarded as outliers (movement duration > mean + 3*SD). All remaining movement durations were averaged per ID for each movement condition and each participant. To obtain insight into motor imagery capacity, temporal congruence between executed and imagined walking was considered. We specifically focused on the effects of task difficulty (represented by different IDs) on the executed and imagined movement durations (Fitts, 1954). ID is a function of target width (W) and target distance (A), via $ID = \log_2(2*A/W)$. First, the effects of movement condition (2 levels) and ID (6 levels) on mean movement durations were tested by means of a repeated measures analysis of variance (ANOVA). Subsequently, to determine the relation between the movement durations of executing and imagining the task, Pearson correlations were calculated. Correlations on both the group mean movement durations as well as on the individual movement durations (averaged per ID) of executed and imagined movements were calculated. Pearson correlations were also used to determine whether age, IQ and level of motor functioning were related to temporal congruence.

Table 7.1

The indexes of difficulty of the six walking trajectories, determined by path length and path width

Path length (cm)	Path width (cm)	Index of Difficulty
225	60	2.91
375	60	3.64
225	30	3.91
375	30	4.64
300	20	4.91
500	20	5.64

Results

Table 7.2 indicates the results of the ANOVA of the movement duration data. Movement durations did not differ between the executed and imagined walking task. As expected, ID affected movement durations. Generally, the duration of the movements increased, when the difficulty of the walking trajectory was higher (Figure 7.1). Importantly, no interaction between ID and movement condition (execution and imagining) was found. This is shown in Figure 7.1, as the increase of the movement durations with increasing IDs is similar among the executed and imagined conditions.

Table 7.2

Statistical results of the effect of movement condition (execution; imagining) and index of difficulty (ID) on movement duration

Effects	***F*** **(df)**	***p***	η^2
Movement condition	(1, 19) = 1.19	0.29	0.059
ID	(5, 95) = 42.0	< 0.001	0.69
ID * Movement condition	(5, 95) = 2.43	0.092	0.11

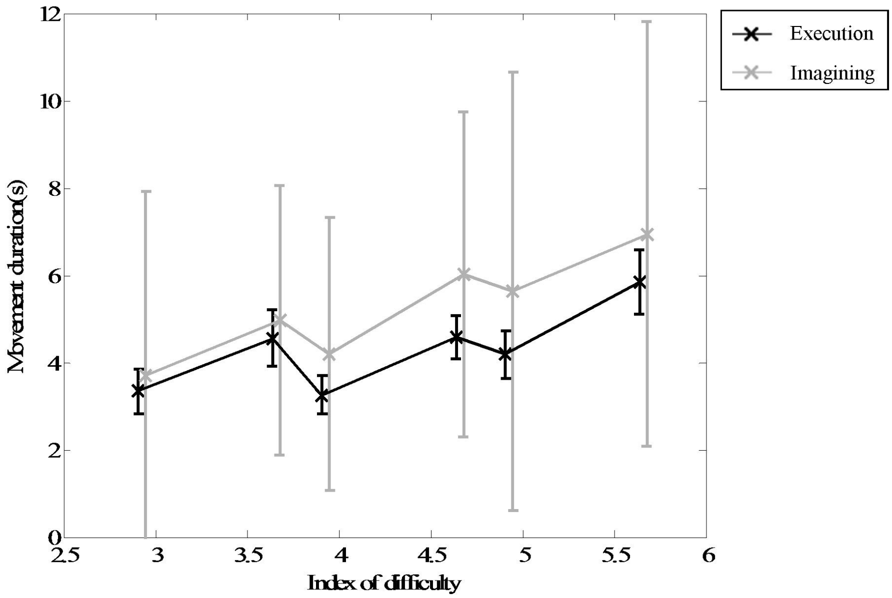


Figure 7.1. Mean movement duration over six indexes of difficulty for the imagery and execution condition (with vertical lines representing the SD).

Mean movement duration per ID for the executed walking correlated significantly with the mean duration per ID for the imagined walking condition ($r = 0.926$, $p < 0.01$) (Figure 7.2). Considering the relation between imagined and executed movement durations for individual participants, the correlations of 13 of 20 participants were significant. Individual correlations ranged from $r = 0.43$ to $r = 0.97$ (mean = 0.83, median = 0.89). Age, IQ and Bocks and Blocks did not significantly correlate with the correlation coefficient reflecting temporal congruence (Table 7.3).

Table 7.3

Correlations between the temporal congruence (correlation between executed and imagined movement durations) and age, IQ and Bocks and Blocks

	r
Age	0.16
IQ	0.09
Box and Blocks, preferred hand	0.36
Box and Blocks, non-preferred hand	0.082

Note: None of the correlations were significant

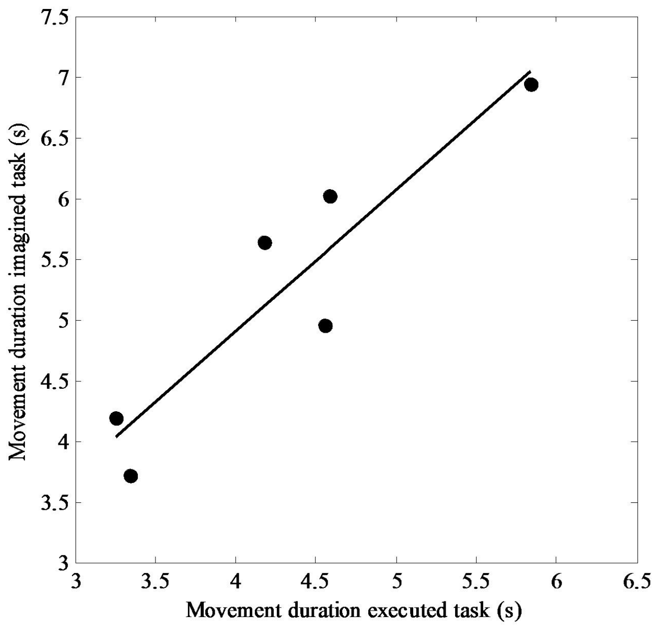


Figure 7.2. Correlation between the mean movement durations of the executed condition and the imagined condition $r = 0.926$, $p < 0.01$. The bullets represent the six indexes of difficulty.

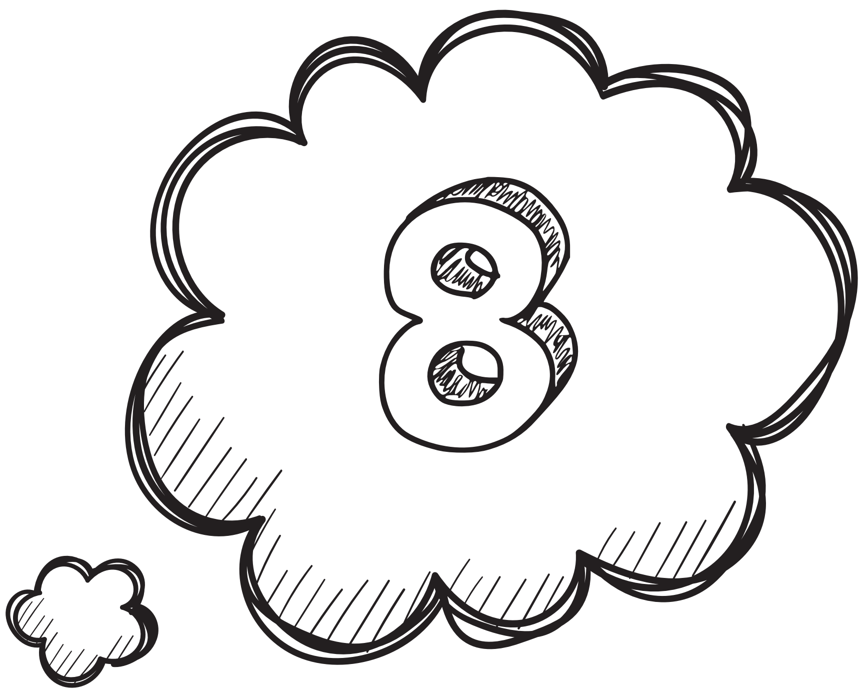
Discussion

In the present study we used a mental chronometry paradigm to examine the motor imagery capacity of individuals with CP. We hypothesized that, owing to the explicit nature of the familiar motor task (a walking task), participants were facilitated to use motor imagery to perform the task. In line with our expectation, it was found that the executed and imagined walking tasks were temporally congruent. First, the ANOVA showed an increase in movement durations as a function of ID, but no interaction with movement condition was found (Figure 7.1). Second, per ID, the mean movement duration in the executed walking correlated significantly with the mean duration in the imagined walking condition (Figure 7.2). Thus, importantly, task difficulty similarly affected movement durations in both the executed and imagined condition in such a way that a higher task difficulty resulted in increased movement durations. The combination of these findings indicates that in the present study, individuals with CP were able to use motor imagery in a walking task. These findings appear to be in contrast with earlier studies on motor imagery in individuals with CP. The results of these studies were equivocal, with some studies suggesting an ability to use motor imagery (e.g., Williams, Anderson, et al., 2011; Williams, Reid, et al., 2011), while other studies reported an impairment in the use of motor imagery in individuals with CP (e.g., Crajé, van Elk, et al., 2010; Williams et al., 2012).

The two most commonly used paradigms to study motor imagery are the hand laterality task and the mental chronometry task. These tasks differ in the extent to which they address the implicit and explicit use of motor imagery. While we showed that the participants used motor imagery in the walking task, we did not compare the results to an implicit motor imagery task. In this respect, the studies of Williams et al. (Williams et al., 2012; Williams, Reid, et al., 2011) may shed light on the use of motor imagery performance among both paradigms (that is, hand laterality versus mental chronometry), as it was clear from the group characteristics of both studies that the same participant group was used. Overall, the effect of rotation angle and biomechanical constraints of the hand stimuli in the hand laterality task indicated the capacity of the group of individuals with CP to use motor imagery (Williams, Reid, et al., 2011). Motor imagery performance did not differ between individuals with left or right unilateral damage. In contrast, applying a mental chronometry task of finger pointing in the same participants showed that participants with left-sided hemiplegia (right sided brain damage) did not use motor imagery, while the participants with right-sided hemiplegia did use motor imagery (Williams et al., 2012). In contrast to our argument, the comparison between both studies suggests that providing explicit task instructions (i.e., the mental chronometry task) does not facilitate the use of motor imagery, compared to the more implicit hand laterality task (Sirigu & Duhamel, 2001), as motor imagery capacity in CP was also shown in the latter task. Crucially, however, Williams, Reid et al. provided the participants with specific instructions in the hand laterality task, to imagine their own hand in the position of the displayed hand. Thus, the, in principle, implicit hand laterality task was made explicit. In line with our argument it is likely that this explicit instruction facilitated the use of motor imagery in the hand laterality task. The suggestion that motor imagery is only facilitated in the hand laterality task when explicit imagery instructions are provided is strengthened by previous studies using the hand laterality task (Crajé, van Elk, et al., 2010; Mutsaarts et al., 2007). In these studies, participants were not specifically instructed to imagine their own hand and the use of motor imagery was not found. In conclusion, the equivocal findings on motor imagery capacity in CP thus far may be due to the paradigm used to assess this capacity.

Familiarity of the motor task (walking) and the explicit nature of the imagery instructions were shown to be crucial features to reveal the true motor imagery capacity in CP. These specific task aspects may also inform rehabilitation efforts using motor imagery training. This type of training was frequently shown to be effective in adults with acquired brain damage, such as stroke (Dickstein & Deutsch, 2007; Malouin & Richards, 2010). Although motor imagery training is theoretically a promising method to also improve motor performance in CP (Steenbergen et al., 2009), its efficacy still awaits empirical testing. For motor imagery training to be effective, young participants with CP need to have the capacity to use motor imagery. The results of the present study indicate that it is crucial to select an appropriate paradigm to assess motor imagery capacity and that a paradigm with explicit measures may be most suitable. Subsequent to establishing the capacity for motor imagery, the actual training may be informed by the present results as well. That is, explicit instructions may be a key factor for efficacy of such training. Traditionally, motor imagery training in patients with acquired brain damage (stroke) typically starts with relaxation exercises, followed by short sessions in which the participant is instructed to imagine certain movements or actions (e.g., Sharma et al., 2006). The efficacy of such an approach has been shown for stroke patients, but it can be questioned whether the protocols used for stroke patients are effective in young individuals with CP. More likely, they would benefit from a training incorporating more guided, or explicit, imagery instructions. One such approach was recently proposed by Sgandurra et al. (2011) and is called Action Observation Therapy. This therapy is based on mirror neurons. Conceptually, it can be argued that this therapy is not motor imagery per se, as it is not solely the imagery of actions, but rather the observations of actions. However, based on the results of the present study, it may be speculated that such a therapy may be more feasible to use in children, also because it does not require elaborate instructions as is the case with imagery training (Sharma et al., 2006).

Finally, although it is known that the CP condition varies in severity and type of the motor impairment (unilateral versus bilateral) among individuals, we have treated participants in the present study as one group. As a group, these participants were able to use motor imagery and we further noted that for 13 of 20 participants the correlations between imagined and executed movement durations reached statistical levels of significance. Thus, individual differences are clearly present. Williams et al. (2012) showed that motor imagery performance might be related to the level of motor function, and for this reason we considered this factor as well. In the present task, however, individual motor imagery performance was not related to the level of motor function. By the same token, motor imagery performance was not related to age or IQ of the individual participants. This first study on the use of mental chronometry of walking in CP was aimed at providing insight into the overall capacity to use motor imagery. Therefore, we did not focus specifically on relating differences in motor imagery performance between participants to, for example, differences in the affected side of the hemiparetic condition (left versus right body side, see Mutsaarts et al., 2007). It is evident that follow up studies are needed to examine the influence of individual factors on the capacity to use motor imagery.


8

Discussion

This thesis examined the early developmental trajectory of children's motor imagery. Obtaining insights into the development of movement representations can facilitate our understanding of motor control processes that can be related to children's motor development, such as motor planning (Jeannerod, 1994). Furthermore, these insights contribute to our understanding of the feasibility of implementing motor imagery training for rehabilitation purposes in children with motor disabilities (Steenbergen et al., 2013). To assess motor imagery in children, two commonly used motor imagery paradigms were employed in the present studies: hand laterality judgments (HLJ task) and mental chronometry. Throughout the thesis, it is emphasized that children can engage in alternative non-motor imagery strategies (such as performing an estimated guess) to perform the experimental tasks. Hence, the overall performance on the imagery tasks does not uniquely reflect motor imagery ability. It was therefore determined whether or not the children actually used motor imagery, by examining whether the performance on the experimental task was grounded in the motor system. For example, on the HLJ task engagement in motor imagery was indicated when biomechanical constraints of hand movements affected the task performance and on the mental chronometry tasks motor imagery use was reflected when task difficulty affected the imagery performance. In this final chapter, it is first discussed what we can learn from our observations on the two experimental tasks about children's motor imagery engagement as a function of age. Additionally, the role of factors that might affect children's engagement in motor imagery on the tasks is considered. Furthermore, I discuss how these observations reflect developmental changes in children's ability to mentally represent movements and how this contributes to our understanding of motor control processes. Finally, the implications of our novel insights for implementing motor imagery training in pediatric rehabilitation are considered.

Age-related motor imagery use on imagery tasks in children

Indications of motor imagery use for performing the HLJ task and mental chronometry tasks

In order to draw conclusions on the effect of age for using motor imagery on the experimental tasks, an overview of our observations on the two employed tasks is presented. First, our findings on the effects of age on the use of motor imagery for judging hand laterality are discussed, both for children who perform the task above chance and for children who do not perform the task above chance at 5 years of age. Second, the observed age effects on motor imagery use for performing the mental chronometry tasks are considered.

Previous HLJ studies generally considered the separate effects of rotation angle and direction on response duration to examine the use of motor imagery. In contrast, we introduced a new method of analyzing the HLJ results that takes into account the cumulative effects of these factors on response duration and accuracy, and that allows for determining age-related differences in the contribution of motor and non-motor imagery strategies for judging hand laterality. In line with previous HLJ studies (Funk et al., 2005; Krüger & Krist, 2009), we observed that children who accurately judged hand laterality were already engaged in motor imagery at age 5. In contrast to some cross-sectional studies reporting age-related increases in the involvement of motor imagery on the HLJ task (Conson et al., 2012; Krüger & Krist, 2009; Toussaint et al., 2013) and other cross-sectional studies reporting that motor imagery involvement decreases with age (Funk et al., 2005; Sekiyama et al., 2014), our cross-sectional and longitudinal results do not provide evidence for either an increasing or decreasing involvement of motor imagery for judging hand laterality between 5 and 8 years of age. Instead, it seems that the contribution of motor imagery remains unchanged in this age range.

Importantly, however, this thesis extended previous studies by examining whether motor imagery was also involved when children did not perform above chance on the HLJ task at age 5 and whether or not improvements in task accuracy across age might be attributed to changes in the employment of imagery strategies. Consistent with what was observed for children performing above chance, the involvement of motor imagery was also found for 5-year-olds who did not perform above chance, as evidenced by an effect of biomechanical constraints on task accuracy. These novel insights provide evidence against the hypothesis that an inability to understand task instructions and/or an inability to access motor representations is responsible for inaccurate hand laterality judgments. Moreover, motor imagery engagement was not found to change across age. Taken together, motor imagery for hand laterality judgments emerges at or before the age of 5 and does not change up to age 8.

The present cross-sectional mental chronometry studies found age-related differences in motor imagery indications (both for pointing and walking movements). This was evidenced by improved temporal congruence and compliance with Fitts' law between 6 and 9 years of age (see also Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Smits-Engelsman & Wilson, 2012). Previous mental chronometry studies commonly included typically developing children as a control group for children with motor disorders and these studies were generally not aimed at scrutinizing the changes in the use of motor imagery as a function of age. Instead, the thesis examined whether or not the use of motor imagery on mental chronometry tasks differed across age. To this aim, it was assessed whether or not task performance of children in single age groups showed indications of motor imagery use (temporal congruence and compliance with Fitts' law). For imagining a pointing movement, no evidence for the motor imagery strategy was found among 6-year-olds and only a small proportion of children were engaged in motor imagery at age 7 and 8. For mental chronometry of walking, a minority of 6-year-olds was already engaged in motor imagery and over half of the children was using motor imagery between 7 and 9 years of age. Taken together, our results imply that the use of motor imagery on mental chronometry tasks improved with age and that motor imagery for walking emerges before motor imagery for pointing, that is, at or before age 6.

Taking the HLJ and mental chronometry observations together, what did we learn about the age-related contribution of motor imagery on the tasks? Studies using the HLJ task and the mental chronometry tasks reveal equivocal results on the age-related use of motor imagery. First, children were already engaged in motor imagery at 5 years of age for judging hand laterality, whereas children started using motor imagery at later age for performing mental chronometry (see also Caeyenberghs, Tsoupas, et al., 2009). This is evidenced by a lack of motor imagery use for imagining pointing movements in the majority of 6- to 8-year-old children. As the HLJ task performance was already grounded in motor processes at 5 years of age, it is unlikely that the lack of motor imagery engagement on mental chronometry tasks at age 6 to 8 can be attributed to an insufficient ability to mentally represent movements. Therefore, it can be concluded that the use of motor imagery on the imagery tasks is probably also influenced by other factors, such as distinct task characteristics. The contribution of other factors for performing imagery tasks is also evident from the observation that 5-year-old children who performed inaccurate hand laterality judgments did use motor imagery. This indicates that motor imagery is not the factor limiting successful HLJ task performance and consequently, other factors might hinder accurate performance on the HLJ task. Second, motor imagery use improved between 6 and 9 years of age on the mental chronometry tasks, whereas the use of motor imagery did not change between 5 and 8 years of age on the HLJ task. Noteworthy, overall HLJ task performance did improve with age (more accurate and faster responses; see also Caeyenberghs, Tsoupas, et al., 2009). This indicates that development of the use of motor imagery is not a necessary factor for task performance to develop. Other factors might impact the development of task performance to a greater extent. The next section addresses the question which factors can possibly affect the development on imagery tasks.

Factors that influence performance on imagery tasks

As described above, results on age-related use of motor imagery were equivocal between imagery tasks, such as earlier indications of motor imagery use on the HLJ task than on mental chronometry tasks. Distinct task characteristics of mental chronometry compared to the HLJ task might obstruct motor imagery use at young age. For instance, the nature of the task (either implicit or explicit) may affect the use of motor imagery. In the HLJ task, motor imagery is implicitly induced and explicit instructions for using motor imagery are typically lacking. In contrast, instructions are more explicit in mental chronometry tasks and make children more aware of the required imagery process (McAvinue & Robertson, 2008). It was previously shown that children's implicit learning

(learning without awareness of what they are taught) is unaffected by age, whereas explicit learning (usually involving explicit instructions) improves with age (Meulemans et al., 1998; Vinter & Detable, 2008). Accordingly, young children might already be able to implicitly use motor imagery, while explicit instructions to use motor imagery might not facilitate its use at young age. Working memory capacity might underlie differences between the implicit HLJ task and explicit mental chronometry tasks. This can for instance be explained by the complexity of the instructions. Whereas the implicit HLJ task comprises a single instruction (i.e., "press the button at the hand side that corresponds with the presented hand picture"), the mental chronometry task comprises a set of multiple instructions about the starting position, the process of imagining the movement and the button press at the end of the imagery. These distinct task instructions place a high demand on working memory and call for a sufficiently large and durable working memory to process the multifaceted information (Duncan, Schramm, Thompson, & Dumontheil, 2012; Steenbergen, van der Kamp, Verneau, Jongbloed-Pereboom, & Masters, 2010). Indeed, working memory has been shown to only affect performance on a serial reaction time task when instructions were explicitly provided and not when the participants did not receive such explicit instructions (Unsworth & Engle, 2005). Insufficient working memory capacity until 6 years of age and gradual development of working memory thereafter (Kemps et al., 2000) might thus explain a lack of motor imagery use and developmental improvements on explicit imagery tasks (i.e., mental chronometry). It is an interesting focus for future studies to determine whether or not working memory indeed differently affects implicit and explicit motor imagery use. This is possible by examining whether working memory capacity only affects the use of motor imagery on the explicit mental chronometry tasks and not on the implicit HLJ task.

The use of motor imagery for performing mental chronometry tasks also seems to depend on the type of motor task that is used to assess motor imagery (Crognier et al., 2013; Fusco et al., 2014; Kunz et al., 2009). Although performances on different motor tasks were not directly compared within a group of children, the identical methods to measure motor imagery ability allowed a comparison between the results of the group of children who performed the pointing task and the results of the group of children who performed the walking task. More distinct indications of motor imagery were observed for walking than for pointing, as evidenced by higher temporal congruence and a stronger effect of task difficulty on imagined movements. Furthermore, children started to use motor imagery at earlier age for walking than for pointing. In line with the above, imagining a pointing movement might be hindered because of the more explicit nature of the sequential pointing task compared to the walking task. Performing a sequence of pointing movements may require the children to adopt a more extensive mental rehearsal strategy than the more implicit single lane walking task. This would explain why stronger indications of mentally representing walking movements were observed, compared to mentally representing pointing movements at young age. Furthermore, better motor imagery performance for walking might be attributed to the experience and familiarity with the motor task (Fusco et al., 2014; Williams, Cumming, & Edwards, 2011). Motor experience leads to building and updating mental representations of movements (Wolpert, 1997), that are involved in motor imagery (Jeannerod, 2001). As children spend more time and are therefore more experienced with walking compared to sequential pointing towards targets, this may also explain why they have better motor imagery performance on the walking task.

Our novel HLJ task results on children who did not perform the HLJ task accurately at young age indicated that these children were actually engaged in motor imagery. It is therefore unlikely that task inaccuracy is caused by an inability to use motor imagery. This raises the question as to what factors hinder the accurate performance on the HLJ task. In a similar fashion, it remains unclear what factors contribute to improved HLJ task accuracy and speed across age, as the use of the motor imagery strategy did not display developmental changes. For instance cognitive abilities such as attention and working memory might be related to performance on the HLJ task. As was previously suggested by Schott (2012), mentally representing hand movements places large demands on attention and working memory, as this cognitive motor process involves the monitoring of action plans in working memory and motor inhibition of the action. Improvements in response accuracy and speed across age might therefore be attributed to developing attention and working memory processes during childhood (Breckenridge et al., 2013; Kemps et al., 2000). Furthermore, as we have shown that IQ was related to the accuracy with which children judge hand laterality, development towards more accurate HLJ task performance might also relate to improved cognitive abilities to follow task instructions and/or better discrimination between left and right. Last of all, inhibitory control might affect performance on imagery tasks, as the motor imagery process involves the inhibition of movement execution (Decety, 1996b). Indeed, we showed that the motor imagery performance on a mental chronometry pointing task was related to inhibitory control (see also Angelini et al., 2015; Guillot et al., 2012). The development of children's inhibitory control (Ikeda et al., 2014) might therefore underlie developmental improvements on imagery tasks and might also explain why children's ability to engage in motor imagery is hindered at young age.

From the above, it can be concluded that the development on imagery tasks is not exclusively determined by the use of motor imagery, but it can also be facilitated or hindered by several other factors that are related to cognitive functioning. These factors may include task characteristics such as explicitness of instructions and the type of motor task, but also executive functions of the participants, such as inhibition and working memory, that are developing during childhood. A challenge remains to clarify the exact role of these factors on developmental changes in children's performance on imagery tasks.

Children's motor imagery development

In order to determine motor imagery development in children, we performed several studies using two different motor imagery paradigms. In the above, the effect of age on children's engagement in motor imagery on the experimental tasks is discussed. However, I argue that task performance does not uniquely reflect motor imagery ability, as other factors might also influence task development and age-related changes in motor imagery engagement. In the present section, it is discussed what can be concluded from our observations about the effect of age on the overall ability of children to mentally represent movements. Where possible, these conclusions are also linked to the developmental changes in motor processes that have previously been described to be associated with motor imagery, such as motor planning (Jeannerod, 1994) and feedforward control (Wolpert, 1997).

Our observations on the HLJ tasks have provided clear indications that 5-year-old children were already engaged in motor imagery, even when the task was performed inaccurately. This leads to the conclusion that mental representations of movements are already formed and can be accessed (at least implicitly) at age 5. These findings are consistent with indications that children can already use motor planning (Weigelt & Schack, 2010) and feedforward control (De Ste Croix & Korff, 2012) around age 5. The thesis was focused on obtaining insight into the early emergence and development of children's motor imagery ability. As we did not consider children that were younger than 5 years of age, it can only be concluded that children start to develop and/or access mental representations of movements at, or before 5 years of age.

Although accuracy and speed on the HLJ task improved across age, the engagement in motor imagery on the HLJ task did not develop between age 5 and 8. In contrast with previous studies showing improved ability to plan movements (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, et al., 2013) and use feedforward control after 5 years of age (De Ste Croix & Korff, 2012), these results might imply that once children are able to mentally represent movements, this ability does not change between 5 and 8 years of age. However, it is discussed above that motor imagery use on the experimental tasks does not uniquely reflect motor imagery ability. Hence, we have to be cautious in drawing conclusions on the general ability of children to mentally represent actions from the present results. A challenge for the future is to examine the intricate relationship between cognitive factors and motor imagery development. At present, both are merely studied in isolation, but this thesis provides clear indications that elements of executive function (such as working memory and inhibition) impact on the capacity to enlist motor imagery. Distinguishing between the contribution of these factors and the contribution of motor imagery ability on motor imagery task performance can facilitate our understanding of motor imagery development in children. Moreover, the challenge remains to develop a method for gaining insight into children's motor imagery development by means of measures that provide a direct reflection of motor imagery ability.

Practical implications for rehabilitation

Motor imagery is functionally equivalent to the planning and execution of a movement (Jeannerod & Decety, 1995) and stimulates the same neural networks that are involved in motor execution (Case et al., 2015). In addition to extensive research on the effect of motor imagery training on adult motor performance (for reviews, see Carrasco & Cantalapiedra, 2013; Dickstein & Deutsch, 2007), some first studies on motor imagery training effects were also conducted in typically developing children. These studies showed that explicitly instructed motor imagery training could promote the performance of finger opposition and throwing movements in typically developing children between 8 and 10 years of age (Asa et al., 2014; Doussoulin & Rehbein, 2011; Taktek et al., 2008). It has been suggested that motor imagery training is also a potential tool for improving motor performance in children with developmental motor disorders (Steenbergen et al., 2009). Indeed, a first study on the effects of mental imagery training on fine and gross motor skills in 7- to 12-year-old children with developmental coordination disorder (DCD) supports the potential for adding imagery training to conventional rehabilitation (Wilson et al., 2002), although the training comprised of a combination of motor imagery and action observation. Before including motor imagery training in pediatric rehabilitation programs, some insights are necessary to judge the feasibility of motor imagery training for children with motor disorders (see also Steenbergen et al., 2013). For instance, as engagement in motor imagery is a prerequisite for the effectiveness of motor imagery training, it is an important first step to establish whether or not children (with motor disabilities) are able to engage in motor imagery in the context of motor imagery training programs.

The present results provided indications that typically developing children are already able to access mental representations of movements in an implicit task at 5 years of age. However, previous studies suggested that motor imagery ability is diminished in children with motor disorders in comparison with a typically developing control group (e.g., Noten et al., 2014; Williams, Anderson, et al., 2011). This thesis therefore also considered whether or not individuals with cerebral palsy (CP) were able to engage in motor imagery. Mental chronometry of walking was used to examine motor imagery engagement of 7- to 19-year-old participants that were experienced in independent walking. As a group, the participants showed temporal congruence and similar effects of task difficulty on the actual and imagined durations, indicating the ability to engage in motor imagery following explicit instructions. Noteworthy, we observed clear individual differences in the engagement in motor imagery that were not related to differences in age or IQ. A challenge thus remains to determine the factors that might have caused individual differences in motor imagery use in this heterogeneous group. Below, it is addressed how insights into the previously discussed task characteristics and personal factors that might impact upon motor imagery use, can be used for implementing motor imagery as a rehabilitation tool in children with motor disorders.

Children with motor disorders such as CP and DCD experience difficulties with motor behaviour to a varying degree. For instance, children with DCD might experience difficulties with everyday activities such as writing and sports due to poor fine and gross motor skills (Wilson & Larkin, 2008). Moreover, children with CP might even lack experiences of everyday activities such as walking, as their motor behaviour is compromised throughout their life as a result of early brain damage (Polatajko & Cantin, 2005). Experience with a movement is necessary to built and update movement representations (Wolpert, 1997) and is therefore a prerequisite for the effectiveness of motor imagery training (Fusco et al., 2014). Hence, it is unlikely that motor imagery training improves motor performance in children that have no experience with the movement that is targeted by the training (see also Mulder et al., 2004). Alternatively, rehabilitation programs are likely to be most effective when targeting movements that are compromised in children with motor disorders, but with which they have ample experience.

The effectiveness of motor imagery training is not only dependent on the type of motor task, but can also be affected by personal factors. Our observations for instance indicate that motor imagery engagement is related to inhibitory control (see also Angelini et al., 2015; Guillot et al., 2012). When children have insufficient control to inhibit motor output during mental rehearsal of a movement, this can obstruct their ability to engage in motor imagery and benefit from motor imagery training. As children with developmental motor disorders often also experience difficulties with inhibitory control (Christ, White, Brunstrom, & Abrams, 2003), it is particularly important to select children with sufficient inhibition for implementing motor imagery training as a rehabilitation tool.

Children with motor disorders also often experience problems with working memory and particularly children with DCD have a high prevalence of attention disorders (Jenks, de Moor, & van Lieshout, 2009; Leonard, Bernardi, Hill, & Henry, 2015; Lewis et al., 2008). It was discussed that working memory and attention might affect children's ability to engage in motor imagery, especially when motor imagery instructions are explicitly provided. Motor imagery training might therefore only be feasible in children with sufficient working memory and attention processes, as training protocols most commonly employ explicit instructions (for a review, see Schuster et al., 2011). Because it might be challenging to develop a motor imagery training that implicitly encourages children to mentally practice specific movements, children with insufficient working memory, attention and/or inhibitory control might alternatively benefit from probing the motor control system by means of observational learning (de Vries et al., 2013). Observational learning can be seen as a form of mental practice, in which neural networks in the brain that are involved in execution of movements are stimulated as a result of observation of movements (Filimon et al., 2007; Grezes & Decety, 2001). Previous studies have shown beneficial effects of action observation on motor performance (Buccino et al., 2012; Sgandurra et al., 2011). It is therefore an interesting challenge for future research to determine whether or not the integration of action observation and motor imagery (see Vogt et al., 2013) is a fruitful addition to conventional rehabilitation programs for children that experience difficulties with following explicit motor imagery instructions.

To conclude, our mental chronometry study of walking in individuals with CP has shown that approximately half of the individuals with CP were able to engage in motor imagery, and therefore met the pre-condition for motor imagery training to affect motor performance. However, careful consideration of the feasibility of motor imagery training in children with motor disorders is in place, as several factors, including motor experience, working memory, attention and inhibitory control might limit motor imagery engagement in these children. It is an interesting focus for future studies to examine the role of these factors on motor imagery engagement of children with motor disabilities, in order to select individuals who might benefit from motor imagery training as a tool for rehabilitation. The next step is to extend the previous mental training study of Wilson et al. (2002) by examining the effect of explicit motor imagery training on motor performance in children with motor disorders, such as CP and DCD. The implementation of motor imagery training is recommended to be tailor-made to the personal characteristics of the child. For instance, matching the nature of task instructions (explicit vs. implicit) and the selection of motor tasks to the individual capacities and experiences of the child can optimize the training results.

Appendix

Samenvatting

Tijdens het levendig inbeelden van bewegingen (motorische inbeelding) worden bewegingen intern gesimuleerd, zonder dat ze daadwerkelijk worden uitgevoerd (Decety & Grezes, 1999; Jeannerod, 1994; Sharma et al., 2006). Motorische inbeelding is gerelateerd aan de activatie van mentale representaties van beweging en vertoont overlap met cognitieve processen die betrokken zijn bij het plannen en uitvoeren van beweging (Jeannerod, 1994). Empirisch bewijs voor deze overlap tussen motorische inbeelding en motor controle processen wordt onder andere geleverd door activiteit in overeenkomstige hersengebieden tijdens het uitvoeren en het inbeelden van beweging. Door de overeenkomst tussen het proces van plannen en controleren van beweging en het proces van inbeelden van beweging, heeft motorische inbeelding potentie als mentale training om beweging te verbeteren. Voor volwassenen is aangetoond dat motorische inbeeldingstraining als aanvulling op conventionele revalidatieprogramma's ter verbetering van de motoriek effectief kan zijn, bijvoorbeeld na een beroerte (Carrasco & Cantalapiedra, 2013). Kinderen met motorische beperkingen kunnen mogelijk ook profiteren van motorische inbeeldingstraining als revalidatiemiddel. Aangezien het levendig kunnen inbeelden van beweging een voorwaarde is voor de effectiviteit van motorische inbeeldingstraining, is het essentieel om vast te stellen of kinderen in staat zijn om motorische inbeelding te gebruiken. De huidige thesis heeft tot doel om meer inzicht te krijgen in het ontwikkelingstraject van motorische inbeelding van kinderen en om te bepalen vanaf welke leeftijd kinderen motorische inbeelding kunnen gebruiken.

Hoofdstuk 2 geeft een overzicht van de huidige kennis uit de literatuur over motorische inbeelding van kinderen zonder motorische problemen. Eerdere studies hebben hoofdzakelijk twee verschillende paradigma's toegepast om motorische inbeelding te meten. In het 'hand lateraliteit'-paradigma wordt een linker of rechter hand gepresenteerd in verschillende oriëntaties. Er wordt bestudeerd of kinderen motorische inbeelding gebruiken bij de beoordeling van de lateraliteit van de gepresenteerde hand. Wanneer biomechanische karakteristieken van daadwerkelijke handrotaties de beoordeling van de lateraliteit van de gepresenteerde hand beïnvloeden, is dit een indicatie van het gebruik van motorische inbeelding. Met het 'mentale chronometrie' paradigma wordt bepaald of de duur van daadwerkelijk uitgevoerde bewegingen en de duur van ingebeelde bewegingen overeen komen, ook wanneer de moeilijkheidsgraad van de taak wordt beïnvloed. Eerdere studies die het effect van leeftijd op motorische inbeelding van kinderen zonder motorische beperking onderzochten, hebben over het algemeen geresulteerd in indicaties van verbetering van motorische inbeelding tussen 5 en 12 jaar oud, maar deze verbetering werd niet altijd gevonden in hand lateraliteit studies. Er zijn indicaties gevonden dat kinderen al vanaf 5 jaar motorische inbeelding gebruiken om de lateraliteit van handen te bepalen, hoewel mentale chronometrie studies vaak pas op latere leeftijd, vanaf ongeveer 10 jaar, indicaties van motorische inbeelding vinden. Deze resultaten zijn gebaseerd op cross-sectionele studies, waarbij kinderen van verschillende leeftijden met elkaar worden vergeleken. Een longitudinale studie naar motorische inbeelding van kinderen is tot dusverre nog niet uitgevoerd.

Hand lateraliteit beoordeling

Hoofdstuk 3 introduceert een innovatieve methode om te bepalen of kinderen tussen 5 en 8 jaar motorische inbeelding gebruiken om de lateraliteit van handen te beoordelen. In overeenstemming met eerdere studies is gevonden dat kinderen minder fouten maakten met toenemende leeftijd tussen 5 en 8 jaar. Ze werden ook sneller in de taak in deze leeftijdsrange. De studie toont aan dat kinderen die accuraat (boven kans) presteerden al vanaf 5 jaar motorische inbeelding gebruikten. Een opvallende bevinding is dat de motorische inbeelding die door de kinderen werd gebruikt om de lateraliteit te beoordelen niet verschilt over de leeftijd. Deze resultaten bieden een belangrijke indicatie dat verbetering van de algemene taakprestatie (accuratesse en snelheid) waarschijnlijk niet wordt veroorzaakt door veranderingen in het gebruik van motorische inbeelding.

Bovenstaande cross-sectionele resultaten worden in **hoofdstuk 4** gerepliceerd met een longitudinaal design, waarbij veranderingen tussen 5 en 7 jaar worden bestudeerd. In deze studie zijn niet alleen kinderen bestudeerd die de taak accuraat (boven kans) uitvoerden, maar is tevens onderzocht of kinderen die op 5-jarige leeftijd nog niet boven kans presteerden al wel motorische inbeelding gebruikten. In overeenstemming met de bevindingen uit hoofdstuk 3 gebruikten de kinderen al op 5-jarige leeftijd motorische inbeelding, zelfs wanneer de taak niet accuraat werd uitgevoerd. Het gebruik van motorische inbeelding blijkt dus niet de beperkende factor te zijn voor het accuraat uitvoeren van de taak. Daarnaast bevestigt de longitudinale studie dat er geen veranderingen optraden in het gebruik van motorische inbeelding tussen 5 en 7 jaar. Dit is niet alleen gevonden voor de kinderen die al op 5-jarige leeftijd accuraat (boven kans) presteerden, maar ook voor de kinderen die op 5-jarige leeftijd nog niet accuraat (op kans) presteerden. Hieruit blijkt dat de overgang van het onsuccesvol uitvoeren van de taak op jonge leeftijd, naar het succesvol uitvoeren van de taak op latere leeftijd niet kan worden verklaard door ontwikkeling van het gebruik van motorische inbeelding. Concluderend kunnen kinderen al vanaf 5 jaar motorische inbeelding gebruiken voor het beoordelen van hand lateraliteit. Hoewel kinderen sneller en accurater worden tussen 5 en 8 jaar, zijn er geen indicaties dat motorische inbeelding ontwikkelt in die leeftijdsrange.

Mentale chronometrie

Hoofdstuk 5 beschrijft een cross-sectionele studie waarbij motorische inbeelding van 6-, 7-, en 8-jarige kinderen is bestudeerd door mentale chronometrie van een conventionele wijstaak. De kinderen maakten wijsbewegingen naar vijf doelen en de moeilijkheid van de taak werd beïnvloed door variatie in de afstand tot het doel en de doelgrootte. De indicaties van het gebruik van motorische inbeelding werden sterker tussen 6- en 8-jarige leeftijd. Op 6-jarige leeftijd werden nog geen indicaties gevonden van het gebruik van motorische inbeelding, maar op 7- en 8-jarige leeftijd gebruikte de minderheid van de kinderen motorische inbeelding. Daarnaast is er een zwak verband gevonden tussen de prestatie op de mentale chronometrie taak en de mate van inhibitie. Dit kan worden verklaard door de rol van inhibitie tijdens motorische inbeelding, aangezien het daadwerkelijk uitvoeren van de beweging wordt geremd wanneer bewegingen mentaal worden gerepresenteerd.

Eerdere studies vonden indicaties dat de prestatie op motorische inbeeldingstaken afhankelijk is van de taak waarmee het wordt gemeten. Ter aanvulling op de wijstaak chronometrie studie (hoofdstuk 5) presenteert **hoofdstuk 6** een chronometrie studie waarin motorische inbeelding van 6- tot 9-jarige kinderen is onderzocht met een looptaak. In overeenstemming met de bevindingen op de wijstaak, worden de indicaties van het gebruik van motorische inbeelding op de looptaak sterker met de leeftijd. Op 6-jarige leeftijd gebruikte al een klein deel van de kinderen motorische inbeelding voor het inbeelden van lopen, en vanaf 7 jaar al meer dan de helft van de kinderen. De sterkere indicaties voor het gebruik van motorische inbeelding voor lopen ten opzichte motorische inbeelding voor wijzen ondersteunt eerdere indicaties dat het gebruik van motorische inbeelding afhankelijk is van de motorische taak. Dit kan mogelijk verklaard worden door de ervaring die kinderen hebben met de beweging.

Deze thesis beschouwt mogelijkheden van motorische inbeeldingstraining voor revalidatie van kinderen met motorische beperkingen. Ter aanvulling op de studies naar motorische inbeelding van kinderen zonder motorische beperkingen, is in **hoofdstuk 7** bestudeerd of kinderen en adolescenten met cerebrale parese (7 tot 19 jaar) motorische inbeelding kunnen gebruiken. Dit is bestudeerd met chronometrie van lopen. De groepsresultaten geven indicaties dat kinderen en adolescenten met cerebrale parese motorische inbeelding kunnen gebruiken. Een belangrijke bevinding is dat niet voor alle individuen indicaties van motorische inbeelding zijn geobserveerd. Er is geen verband gevonden tussen enerzijds taakprestatie en anderzijds leeftijd en IQ. Voor vervolgonderzoek is het interessant om te bepalen welke factoren het gebruik van motorische inbeelding faciliteren of hinderen, zodat kan worden bepaald welke kinderen met motorische beperkingen kunnen profiteren van motorische inbeeldingstraining.

Tot slot

De resultaten uit deze thesis tonen aan dat kinderen op een impliciete hand lateraliteit taak al op 5-jarige leeftijd bewegingen mentaal kunnen representeren. In tegenstelling tot resultaten op de expliciete mentale chronometrie studies die een ontwikkeling van het gebruik van motorische inbeelding aantonen, zijn er geen indicaties van ontwikkeling van motorische inbeelding gevonden in de hand lateraliteit studies. De discrepantie in resultaten op de verschillende inbeeldingstaken suggereert dat de taakprestatie niet alleen wordt bepaald door de mogelijkheid om bewegingen mentaal te kunnen representeren, maar dat andere factoren ook van invloed kunnen zijn (**hoofdstuk 8**). Mogelijke factoren zijn inhibitie, aandacht en werkgeheugen. Hoewel sommige kinderen met motorische beperkingen in staat zijn om motorische inbeelding te gebruiken, is een voorzichtige houding ten opzichte van het toepassen van motorische inbeeldingstraining als revalidatiemiddel voor kinderen op zijn plaats. Een belangrijke vervolgstap is het identificeren van factoren die het gebruik van motorische inbeelding faciliteren of hinderen. Deze factoren kunnen worden gebruikt om kinderen te selecteren die mogelijk kunnen profiteren van motorische inbeeldingstraining. Daarnaast is het vaststellen van deze factoren van belang voor het aanpassen van de training aan de persoonlijke situatie van de kinderen, bijvoorbeeld op instructieniveau en voor het selecteren van de beweging die getraind gaat worden.

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About the author

Steffie Spruijt was born on the 20th of August in Hoogblokland, a tiny village in the Netherlands. She studied Human Movement Sciences at the University of Groningen. After the bachelor of science (2005-2008), she enrolled in the masters program: Rehabilitation and functional recovery (2008-2010). Steffie performed her master research project at Roessingh Research and Development, a research institute that is internationally known for its contribution to the field of rehabilitation technology. For her research project (supervised by Raoul Bongers and Gerdienke Prange), she performed EMG measurements to study muscle synergies of reaching movements in older adults after stroke. In 2011, Steffie started her PhD on motor imagery development in children at the Behavioural Science Institute. The present thesis is the result of this research. Currently, Steffie works as national coordinator at ClaudicatioNet, a healthcare network that aims at transparent and high-quality care for patients with intermittent claudication.

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