# On the link between action planning and motor imagery: a developmental study

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| Keywords: | motor imagery, motor planning, end-state comfort, primary school children |
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# On the link between action planning and motor imagery: a developmental study

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## Abstract.

We examined the link between action planning and motor imagery in 6- and 8-year-old children. Action planning efficiency was assessed with a bar-transport task. Motor imagery and visual imagery abilities were measured using a hand mental rotation task and a number (i.e., non-body stimuli) mental rotation task, respectively. Overall, results showed that performance varied with age in all tasks, performance being progressively refined with development. Importantly, action planning performance was correlated with motor imagery ~~at 6 years~~, whereas no relationship was evident ~~for the oldest children as well as~~ between action planning and visual imagery at any age. The results showed that ~~for 6-year-old children,~~ the ability to engage sensorimotor mechanisms when solving a motor imagery task was concomitant with action planning efficiency. The present work is the first demonstration that evaluating the consequences of the upcoming action in grasping depends on ~~the 6-year-old~~ children's abilities to mentally simulate the response options to choose the most efficient grasp.

## Keywords.

Motor imagery, motor planning, end-state comfort, primary school children.

## Introduction

Interactions with the environment contribute to human development. Many of these interactions involve the handling of multiple objects. Objects can be manipulated through different actions, which depend on goals, environmental constraints and motor skills. For instance, Rosenbaum and collaborators (Rosenbaum and Jorgensen 1992; Rosenbaum et al. 1992, 2001) reported that one major constraint on the movement selection for object manipulation in adults is the *end-state comfort effect*. This effect illustrates the spontaneous tendency to plan a comfortable position at the end rather than at the beginning (start-state comfort) of manual object manipulation to maximize the final phase of movement efficiency or to facilitate future actions. In other words, the adopted posture when grasping an object depends on what participants plan to do with it, which reveals anticipations of their future bodily states.

The end-state comfort effect was examined in various developmental studies both in infants and children (Adalbjornsson et al. 2008; Crajé et al. 2010a; Janssen and Steenbergen 2011; Jovanovic and Schwarzer 2011; Manoel and Moreira 2005; McCarty et al. 1999, 2001; Thibaut and Toussaint 2010; Weigelt and Schack 2010). Although there is some evidence that 19-month-old infants took into account the demands associated with the goal of action when they had to grasp a familiar object with either their preferred or non-preferred hand (McCarty et al. 1999, 2001), sensitivity to end-state comfort (vs. start-state comfort) develops later on in childhood for unfamiliar object manipulation. Specifically, the end-state comfort effect starts to be seen only at 4-5 years of age (Crajé et al. 2010a; Weigelt and Schack 2010) and improves with age, as reported by Thibaut and Toussaint (2010). In their study with 4- to 10-year-old children, Thibaut and Toussaint (2010) used a unimanual bar transport task and demonstrated that most children used overhand grips when these grips were consistent with end-state comfort. By contrast, when underhand grips coincided with end-state comfort, only

10-year-old children used these grips in the majority of the cases. Interestingly, however, younger children displayed clear-cut preferences: they chose either underhand grips in all of the trials or failed in all of the trials, without adapting their behavior during the task.

Altogether, these studies confirm the increase in end-state comfort with age. However, the sensitivity towards comfortable end-states during childhood may be affected by several factors. The *task constraints* could explain that action planning may be easier for some children (Thibaut and Toussaint 2010). From 8 years, for example, end-state comfort increases when the task affords a set of clearly defined constraints, showing that these children are able to accurately analyse all of the information of the task to successfully plan their action. Recently, Knudsen et al. (2012) reported that the *familiarity of the objects* to manipulate might determine children's ability to plan their action according to end-state comfort. The *action-effect associations* can also affect end-stat comfort, by helping the children to plan their action more efficiently due to higher motivation to accomplish the task (i.e., when action leads to relevant effects in the environment; Jovanovic and Schwarzer 2011; see also Janczyk et al. 2012; Knudsen et al. 2012). Interestingly, another factor that might affect end-stat comfort performance during childhood might be *motor imagery capacity*. End-state comfort effectively suggests that the participants anticipated their future bodily states to satisfy the intended action goal. This body anticipation throughout imagery means that children must be able to implicitly simulate action to anticipate end-state comfort. Thus, it may be possible that implicit motor imagery capacity plays a determinant role in the children ability to efficiently plan their action. In the present experiment, we specifically investigated the link between implicit motor imagery capacity and action planning efficiency in 6- and 8-year-old children.

Motor imagery is the ability to mentally simulate an action without executing it (Jeannerod 1999). Motor imagery thereby provides a window into the process of action representation and becomes a potential tool to investigate the development of action representation during childhood. Implicit motor imagery ability can be measured with a hand mental rotation task (Parsons 1994). In this task, participants had to determine whether hand pictures presented at different orientations corresponded to a left- or a right-hand rotation. Parsons (1994) reported that response times increased as a function of the rotation angle of the hand stimulus, indicating that the participants used their mental rotation capacities to solve the task. Importantly, unlike visual imagery, mental rotation processes used to solve the hand laterality task are dependent on biomechanical constraints; response times further increased when the simulated actions fit with the most awkward or biomechanically difficult postures (Ni Choisdealbha et al. 2011; Nico et al. 2004; Parsons 1994; Sekiyama 1982). In this respect, Ni Choisdealbha and collaborators (2011) reported increased response times for *lateral* orientations (i.e., fingers pointing away from the body's midline) rather than for *medial* orientations (i.e., fingers pointing towards the body's midline). The evidence for motor mechanisms in mental rotation is also supported by neuroimaging studies. Significant motor cortex activation was observed when participants imagined the rotation of an object as a consequence of their own manual action (Kosslyn et al. 2001b), or when the mental rotation task implies body parts stimuli (Kosslyn et al. 1998, 2001a).

Recent studies have shown that the ability to explicitly generate motor images emerges in children about 5-6 years and is progressively refined during childhood and adolescence (Caeyenberghs et al. 2009; Choudhury et al. 2007a, 2007b; Frick et al. 2009; Gabbard et al. 2009; Molina et al. 2008; Skoura et al. 2009; see also Gabbard et al. 2013, for a recent review). These studies reported an age-dependent increase in the correlation between executed and imagined actions. However, being able to mentally simulate an action does not mean that a motor imagery strategy would be spontaneously used to behavioral purposes if no specific instruction is given to children, especially if motor imagery processes are not yet fully efficient, which is the case for children before 6 or 7 years of age. Currently, there are few developmental studies on implicit motor imagery (Funk et al. 2005), and most of them compared normally developing children to those with atypical development (Deconinck et al. 2009; Williams et al. 2006; Wilson et al. 2004). Overall, results revealed that mental rotation processes used to solve the hand mental rotation task are more dependent on biomechanical constraints for healthy children than for children with abnormal levels of motor skill. However, only 60 % of the healthy children aged about 6 years were able to spontaneously use a motor imagery strategy, compared to 100 % of adults (Funk et al. 2005). Consequently, with age, children incorporate more motor constraints when mentally rotating hand stimuli (Krüger and Krist 2009).

Studies on brain-damaged patients (Crajé et al. 2010b; Johnson 2000a) and on neuroimaging (Johnson et al. 2002) have suggested that motor imagery and action planning are closely related in terms of cognitive processes. Crajé and colleagues (2010b) found that adults with hemiparetic cerebral palsy had both impaired planning and impaired motor imagery processes (see also Mutsaarts et al. 2007). Impaired planning was reflected by the uncomfortable end postures during grasping. Impaired motor imagery was suggested in the participants with cerebral palsy by the similarity of reaction times for the lateral and the medial stimuli orientations because response times were higher for the lateral orientations (i.e., for the most biomechanically constraining movements) in the healthy control participants. The involvement of motor imagery processes in action planning was also highlighted by Johnson (2000b) in a prospective action judgment task in healthy adults. As for real movements, prospective judgments were highly sensitive to biomechanical demands. Moreover, the response times of prospective judgments increased as a function of the awkwardness or the difficulties of the would-be selected grip. These findings support the view that prospective judgments were based on motor imagery to evaluate the efficiency of the potential response options because no actual movements were performed. These results are consistent with the imagery as planning hypothesis, suggesting that motor imagery could be involved during the elaboration of the premotor plan (i.e., during the planning process of action) rather than being dependent on a (fully) completed premotor plan that would be inhibited (Jeannerod 1999). Thus, motor imagery may contribute to solving the problem of how to efficiently grasp an object to anticipate the result of the upcoming movement (Johnson 2000b).

Overall, these studies support the hypothesis that motor imagery may play an important role in solving the problem of movement selection. However, to the best of our knowledge there is no evidence of a direct relationship between motor imagery capacity and action planning efficiency in healthy participants (in children or adults). Because, as is mentioned above, developmental studies have revealed that action planning efficiency (i.e., the end-state comfort effect) increases with age (Adalbjornsson et al. 2008; Crajé et al. 2010a; Janssen and Steenbergen 2011; Manoel and Moreira 2005; Thibaut and Toussaint 2010; Weigelt and Schack 2010) it is important to examine whether grip selection performance is associated with motor imagery capacity in children. Along these lines, in the present experiment, we evaluated motor imagery capacity in 6- and 8-year-old children with a hand mental rotation task. At the same time, we evaluated action planning using a unimanual bar transport task (see Thibaut and Toussaint 2010, for a similar procedure). We predicted that the least efficient action planning children (i.e., few grips consistent with end-state comfort) would show lower motor imagery capacity than the most efficient children. To ensure that less efficient action planning was specifically linked with difficulties in mentally simulating an action and not with general mental imagery inter-individual differences, we asked children to solve an additional mental rotation task using alphanumeric stimuli, which are known to involve visual imagery processes (See Deconinck et al. 2009, for a similar procedure). It was hypothesized that differences in action planning efficiency would be specifically linked to performance in the motor imagery task (vs. visual imagery task). Moreover, in the present experiment, two age-groups (6- and 8-year-old children) have been used to also examine whether motor imagery capacity and action planning efficiency would become more or less tightly coupled with age.

## Method

### Participants

Sixty-four right-handed children participated in the experiment. There were 32 children in each age group: the 6-year-olds (M = 5.9 years, range 5.3 to 6.1; 15 boys and 17 girls) and the 8-year-olds (M = 7.8 years, range 7.2 to 8.2; 18 boys and 14 girls). Informed consent was obtained from the schools and from the children's parents before the experiment. None of the children had any known motor or neurological deficits. The children had normal or corrected-to-normal vision. We systematically screened for handedness by asking children to write their names on a sheet of paper.

### Tasks and procedure

All of the children performed 3 tasks: two mental rotation tasks (i.e., a *visual imagery task* followed by a *motor imagery task*), and an *action planning task*. The order of presentation of the two mental rotation tasks was chosen to avoid the transfer of motor imagery processes into the visual imagery task (Wraga et al. 2003).

#### *Two mental rotation tasks*

The children were seated in front of a 15.4" computer screen at a distance of 40-50 cm. The mental rotation tasks consisted of the children identifying stimuli displayed at the center of the screen by pressing the appropriately marked keys on the keyboard. Each trial began with a black fixation cross being displayed on the center of the screen for 500 ms, followed by a 1000 ms blank screen before the stimulus appeared. Each stimulus remained visible until the child's response was given.

In the *visual imagery task*, the children had to indicate whether an Arabic numeral (i.e., the numeral "2", of the size 4.5 x 3 cm) was presented in its normal form or as its mirror image (Fig. 1b), by pressing the appropriate keys marked with green (key "l") and red stickers (key "s"), respectively. In the *motor imagery task*, children had to decide whether a hand figure (created with Poser 6.0 software, of the size 11 x 6 cm) was a left or a right hand (Fig. 1a), by pressing the left red key for left hand stimuli (key "s") with the left hand or the right green key for right hand stimuli (key "l") with the right hand. For both mental rotation tasks, stimuli were presented in different orientations in the picture plane: at 40°, 80°, 120° and 160° in a clockwise or in a counterclockwise direction. Note that, for the motor imagery task, a clockwise direction corresponds to a *medial orientation* for the left hand and a *lateral orientation* for the right hand, whereas the reverse is true for counterclockwise directions.

---------- *Fig. 1 approximately here* ----------

For all of the children, the two mental rotation tasks were divided into two phases. The first training phase was designed to familiarize the children with each task. They were shown 16 trials (2 Hand or Number x 4 Rotation x 2 Direction) in a random order. No time constraint was imposed during the training phase. During the second experimental phase, the children were shown 4 blocks of 16 randomly presented trials (i.e., 64 trials per child). The children had to respond as accurately and as quickly as possible. No specific imagery instructions were given from the beginning to the end of the experiment. Children were asked whether the stimulus was the correct (number "2") or the wrong way around in the visual imagery task, and whether the hand stimulus was a left or a right hand in the motor imagery task. We used the E-prime© software package to present the stimuli and to record the children's responses (response time and accuracy).

*Action planning task*

The apparatus (Fig. 1c) was similar to the one used by Thibaut and Toussaint (2010, Experiment 1). It was composed of a wooden bar (length: 20 cm, diameter: 1.5 cm, weight: 40 g) colored blue at one end and red at the other end (4 cm); the blue end of the bar was always on the right and the red end on the left, from the child's perspective. The bar rested on two supports (14 cm apart). The distance between the bottom edge of the bar and the table was 7 cm. The children could pick the bar up easily without touching the table with their hand. Two white and black flat disks (6 cm in diameter) were set on the left and right sides of the supports (9 cm apart), respectively.

At the beginning of each trial, the children were asked to put their hands (palms down) on their knees. Children were told that they would have to grasp the bar firmly with their right hand before they place the specified colored end of the bar (i.e., the blue-end or the red-end) on the center of either the white or the black flat disk. The bar would stand up vertically by itself for more than a couple of seconds. Each child performed five blocks of four randomly presented trials (the blue-end or the red-end on the white or on the black disk). For each trial, the experimenter recorded whether the grip was consistent with end-state comfort. Note that efficient grips (i.e., grips that ensure end-state comfort) correspond to an *underhand* grip when the red end of the bar had to be placed on either the white or the black disk and to an *overhand* grip when the blue end of the bar had to be placed on the disks.

## Results

### *Action planning task*

We computed the percentage of overhand and underhand grips that were consistent with end-state comfort. The *percentages of success* for the action planning task were submitted to a 2 Age (6 vs. 8 years) x 2 Target grip (overhand vs. underhand) ANOVA with repeated measures on the last variable. The percentage of correct grips varied with Age, $F(1,62) = 7.58$, $p < .008$, $\eta_p^2 = 0.11$, and Target grip, $F(1,62) = 42.54$, $p < .0001$, $\eta_p^2 = 0.41$. A significant Age x Target grip interaction, $F(1,62) = 6.70$, $p < .012$, $\eta_p^2 = 0.10$ was also observed. The breakdown of the interaction (Tukey test) revealed that the percentage of correct *underhand* grips was significantly lower for the 6-year-old children than for 8-year-old children ($p<.001$), whereas no difference appeared for *overhand* grips (Fig. 2). These results are consistent with those reported by Thibaut and Toussaint (2010): action planning efficiency increased with age for underhand grips (i.e. for the less easy trials for which the grasp was not consistent with the initial palm down hands position).

---------- Fig. 2 approximately here ----------

### *Mental rotation tasks*

Before examining the correlation between action planning and mental rotation (motor and visual imagery tasks), we first examined whether 6- and 8-year-old children exhibited different patterns of response in the motor imagery task and in the visual imagery task.

- *Motor imagery task*

In this section, we examined the effect of age in the motor imagery task. Recall that in the hand laterality task, an imagery strategy engaging motor processes would be highlighted by higher response times or more errors for the lateral orientation than for the medial orientation (i.e., there were differences between the most and the less biomechanically constraining movements, respectively; Crajé et al. 2010b; Mutsaarts et al. 2007; Ni Choisdealbha et al. 2011). We computed accuracy scores (i.e., the percentage of correct responses) and response times for each child. For response times, we included only the data for the correct responses. Accuracy scores and response times were submitted to a 2 Age (6 vs. 8 years) x 4 Rotation (40°, 80°, 120°, 160°) x 2 Orientation (medial vs. lateral) ANOVA with repeated measures on the last two variables.

Results showed that *accuracy scores* varied with Age, $F(1,62) = 21.46$, $p < .0001$, $\eta_p^2 = 0.26$, Rotation, $F(3,186) = 9.76$, $p < .0001$, $\eta_p^2 = 0.14$, and Orientation, $F(1,62) = 12.23$, $p < .0008$, $\eta_p^2 = 0.17$. There was no significant interaction (*ps* > .12). The results revealed that accuracy scores were lower at 6 (69 ±13%) than at 8 years of age (88 ±10%), and were lower for the lateral orientations (73 ±14%) than for the medial orientations (84 ±11%). A subsequent polynomial analysis revealed that accuracy scores significantly decreased with the angular rotation increase of hand stimuli, $F(1,62)=17.68$, $p < .0001$ (40°=82±13%; 80°=81±12%; 120°=78±13%; 160°=74±12%).

*Response times* varied with Rotation, $F(3,186) = 43.93$, $p < .0001$, $\eta_p^2 = 0.41$, increasing linearly with rotation angles, $F(1,62)=92.90$, $p < .0001$ (Figure 3, left graph). A significant effect of Orientation, $F(1,62) = 41.30$, $p < .0001$, $\eta_p^2 = 0.40$, was observed, as well as a significant Age x Orientation interaction, $F(1,62) = 6.93$, $p < .011$, $\eta_p^2 = 0.10$. The breakdown of the interaction (Fig. 4) revealed that response times for medial orientation stimuli were higher for 6- than for 8-year-old children (Tukey test; $p < .05$), while no age differences appeared for lateral orientation ($p$ = .96). Note that response times were smaller for medial than for lateral orientation stimuli for both 6- and 8-year-old children ($ps$ < .05), although the difference between lateral and medial orientation was higher for the older children.

Finally, the slope of the linear function between response times and rotation angles were computed for each child. Individual regression slopes were analyzed using a 2 Age (6 vs. 8 years) x 2 Orientation (medial vs. lateral) ANOVA with repeated measures on the last variable. Results revealed that individual regression slopes tended to be steeper at 8 (329 ms/40°) than at 6 years of age (221 ms/40°), $F(1,62) = 3.57$, $p = .062$, $\eta_p{}^2 = 0.05$, and for medial (319 ms/40°) than for lateral (230 ms/40°) orientations, $F(1,62) = 3.43$, $p = .068$, $\eta_p{}^2 = 0.05$. No significant Age x Orientation was observed ($p$ = .45). Note that the steeper slopes for the 8-year-old children were due to lower response times for the weakest rotation angles compared to the youngest children (Figure 3, left graph).

---------- Fig. 3 and Fig. 4 approximately here ----------

- *Visual imagery task*

Finally, we calculated accuracy scores and response times in the visual imagery task. For response times, we included only the data for the correct responses. Accuracy scores and response times were submitted to a 2 Age (6 vs. 8 years) x 4 Rotation (40°, 80°, 120°, 160°) x 2 Orientation (clockwise vs. counterclockwise) ANOVA with repeated measures on the last two variables.

*Accuracy scores* varied with Age, $F(1,62) = 8.26$, $p < .005$, $\eta_p{}^2 = 0.12$ and Rotation, $F(3,180) = 6.26$, $p < .0004$, $\eta_p{}^2 = 0.09$. Accuracy scores were lower at 6 (69 ±13%) than at 8 years of age (83 ±11%) and linearly decrease with rotation angles increase, $F(1,62)=9.58$, $p <$

.003 (40°=80±11%; 80°=77±12%; 120°=73±13%; 160°=72±12%). There were no other significant main effects or interactions (*ps* > .23).

*Response times* varied with Rotation, $F(3,186) = 13.77$, $p < .0001$, $\eta_p^2 = 0.18$. A significant interaction was also observed between Age and Rotation, $F(3,186) = 5.04$, $p = .002$, $\eta_p^2 = 0.07$. Subsequent polynomial analyses revealed a linear increase in response times with rotation angles for 8-year-old children, $F(1,62)=40.88$, $p < .0001$, but not for 6-year-old children, $F(1,62)=2.68$, $p=.11$ (Fig. 4). There were no other significant main effects or interactions (*ps* > .13).

Finally, the slope of the linear function between response times and rotation angles were computed for each child and analyzed using a 2 Age (6 vs. 8 years) x 2 Orientation (clockwise vs. counterclockwise) ANOVA with repeated measures on the last variable. Results revealed that individual slopes were steeper at 8 (330 ms/40°) than at 6 years of age (85 ms/40°), $F(1,62) = 11.31$, $p < .0013$, $\eta_p^2 = 0.16$. As for the motor imagery task, the steeper slopes for the 8-year-old children were due to lower response times for the weakest rotation angles (Figure 3, right graph). No other significant effect appeared (*ps* > .12)

*Relationship between action planning efficiency and mental rotation tasks*

To gain insight into how the ability to plan motor actions changes with age, Spearman correlation between efficiency of action planning (for underhand grips) and the individual slope of the mental rotation tasks (motor and visual imagery tasks; see Pfister et al, in press, for methodological details) were calculated within each age group. The slope of the mental rotation tasks rather than response times was retained because it was considered as a key measure of mental rotation processes (Shepard and Cooper 1982; see also Badets et al 2013, for a similar procedure). Results are illustrated on Table 1. There was no significant

Spearman correlation between action planning and the visual imagery task. On the contrary, action planning efficiency was positively and significantly correlated with the slope of the motor imagery task for the 6-year-old group. No significant Spearman correlation appeared in the ~~oldest~~older group (*p* = .095), although the performance evolve in the same way as those of the younger children (i.e., positive correlation). Moreover, the Fisher's r-to-Z transformation used to test the difference between the correlation coefficients obtained for both age groups showed no significant effect [*Z*=0.43, *p* = .33]. These results suggested that better action planning was associated with the highest slope values ~~especially for the youngest children~~ in the two age groups considered in the present study. Subsequent Spearman correlation analyses revealed that action planning efficiency was significantly correlated with the lateral versus medial differences in the motor imagery task for the 6-year-old children [*r*=.47, *t*(32)=2.65, *p* < .012]. Note that the difference between lateral and medial orientations for hand stimuli allowed evaluating children's abilities to engage sensorimotor processes in the motor imagery task (Ni Choisdealbha et al. 2011; Parsons 1994). Therefore, these findings support the claim that sensorimotor processes correlate with action planning in young children.

---------- Table 1 approximately here ----------

## Discussion

The main purpose of the present experiment was to determine whether action planning and motor imagery were linked in primary school children. Because action planning efficiency (or the end-state comfort effect) changes during childhood between 4 and 10 years of age (Thibaut and Toussaint 2010), we tested the effectiveness of advanced planning processes in 6- and 8-year-old children with a unimanual bar transport task; we also tested their motor imagery capacities by means of a hand mental rotation task. A visual imagery task was also used to differentiate specific motor imagery processes from general imagery processes in children. The results revealed specific developmental trends for action planning, motor and visual imagery performance. Importantly, they clearly showed that action planning efficiency and motor imagery ability are closely related cognitive processes in ~~the youngest~~ primary school children, whereas no such relationship appeared between action planning efficiency and visual imagery at any age.

The main results observed in the *action planning task* confirmed previous works (Thibaut and Toussaint 2010). Most of the children used the overhand grip when it was consistent with end-state comfort (i.e., with the easy trials for which the palm down position of the hand on the knee was compatible with the position of the hand during grasping). By contrast, fewer children grasped the bar efficiently when the end-state comfort implied an underhand grip. Moreover, accuracy scores of underhand grips revealed that the end-state comfort effect was lower in the 6-year-old group than in the 8-year-old group. These data confirmed the developmental trend of action planning in primary school children highlighted by Thibaut and Toussaint (2010) in a similar bar transport task.

For the *motor imagery task*, the response time and errors increase with rotation angle for both age groups showed that all children were indeed performing mental rotation (Parson 1994). Moreover, the results support the influence of motor mechanisms in mental rotation for 6- and 8-year-old children. The children made more errors and had longer response times for the lateral orientations than for the medial orientations (i.e., for the most difficult postures), as was previously observed in adults (Ni Choisdealbha et al. 2011, Nico et al. 2004; Parsons 1994). Note however that response times differences between medial and lateral orientation was higher for the ~~oldest~~older children, due to their ease to mentally simulate the less constraining movements when compared with younger children, as suggested by their shorter response times for medial orientation stimuli. The larger medial/lateral difference between 6- and 8-year-old children highlighted the development of motor imagery ability with age, higher abilities to engage sensorimotor processes in the motor imagery task being observed for the ~~oldest~~older children. These results corroborate those from Caeyenberghs et al. (2009) who reported a gradual progression during childhood (from 7 to 12 years) in the ability to form motor images by examining the coupling between executed and imagined movement. The interest of our present experiment using a hand mental rotation task was to evaluated motor imagery ability development by specifically examining the evidence for motor mechanisms in mental rotation at various ages.

For the *visual imagery task*, although accuracy scores decreased when stimuli rotation angles increase for all children, a significant linear increase of response time with angle rotation appeared for the ~~oldest~~older children only. As for motor imagery, this developmental change could represent improved processing speed and/or improved visual imagery capacities between 6 and 8 years. These results did not support findings by Estes (1998) who reported that 6-year-old children were similar to adults in their use of visual mental rotation. However, because they used child-friendly images in their mental rotation task, they might have failed to find age differences which became more apparent with the stimuli used in our experiment (number 2 and its mirror image).

Overall, children's performance evolved with age in all tasks, performance being progressively refined with development. The key question, however, is whether mental imagery and action planning processes are closely related in terms of cognitive processes? The correlation analyses showed that ~~for the youngest children,~~ motor imagery ability and action planning efficiency were ~~strongly~~ related in our two groups of children. The present results are consistent with recent experiments involving adults with Hemiparetic Cerebral Palsy (Crajé et al. 2010b). The action planning deficit in HCP patients, illustrated by inefficient grip selection, was concomitant with motor imagery deficits highlighted by atypical response time patterns in the hand laterality task when compared with the healthy control group. In the same vein in the present experiment, less efficient action planning performance for ~~6-year-old~~both groups of children was concomitant with lesser abilities to engage sensorimotor mechanisms~~ when compared with 8-year-old children~~.

The ~~strong~~ relationship between motor imagery ability and action planning efficiency may suggest that motor imagery could be involved during the elaboration of the planning process of action. As previously suggested by Johnson (2000b) in a prospective judgment task with healthy adults, the integration of motor constraints in motor imagery for younger children in the present experiment may induce more efficient action planning, most likely because the evaluation of the consequences of the upcoming action in grasping necessitates, early during childhood, that children are able to mentally simulate the response options to choose the most efficient grasp (overhand versus underhand grip).

~~However, does the absence of significant relationship between motor imagery and action planning for the older group mean that~~Does connection between motor imagery and action planning processes becomes weaker or stronger with age? Unfortunately, the present experiment does not allow answering this question. Although correlation between action planning and motor imagery was statistically significant for 6-year-old children only, the *r*-values (Table 1) indicated similar medium-sized effects for both groups ($Z$=0.43, $p$ = .33). It may be possible that the macroscopic aspect of the action planning task (i.e., the end-state comfort effect) was sufficiently mastered by the 8-year-old children so that a weaker ~~no~~ link between action planning efficiency and motor imagery ability appeared. Consequently, although no specific answer on whether action planning and motor imagery become more or less tightly coupled with age, the present work is the first demonstration of a close link between motor planning and motor imagery capacities in our two groups of children.

One interesting remaining issue concerns the origin of individual differences regarding the link between motor imagery and motor planning in our children ~~observed for 6-year-old children~~. It may be possible that the origin of individual differences comes from the individuals' sensorimotor experiences. In a recent study, Flusberg and Boroditsky (2011) showed that motor imagery processes were affected by previous participants' real world experiences. Their study confirmed the tight coupling between real and imagined actions and suggested that motor imagery is constituted by the reinstantiation of the sensorimotor processes that the participants stored in long term memory as a result of their sensorimotor experiences (see also Toussaint and Blandin 2010, for a similar interpretation in motor learning). Consequently, considering both the data of our present experiment and the data linking motor imagery with previous sensorimotor experiences, further studies could be performed to test whether an increased-sensorimotor experience may induce motor imagery improvement in children and thus facilitate the tight coupling between motor imagery and motor planning efficiency.

To conclude, the present experiment suggests that efficient action planning may depend on motor imagery ability. Healthy children who were the least efficient on ensuring end-state comfort in the grip selection were also those who did not easily engage motor processes in the motor imagery task. Whether these findings lend support to the hypothesis of a weaker connection between sensorimotor and imagery processes in child development (Funk et al. 2005) could be relevant question and need to be studied in the future.

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## Table and figure captions

**Table 1** Correlation between action planning efficiency and the slopes of the motor and visual imagery tasks (p-values)

**Fig. 1** Examples of stimuli used **a)** in the motor imagery task and **b)** in the visual imagery task. Stimuli were presented in different orientations (at 40°, 80°, 120°, 160° in clockwise (CW) and counterclockwise (CCW) directions). Note that, for the motor imagery task, a clockwise direction corresponds to a *medial orientation* for the left hand and a *lateral orientation* for the right hand, whereas the reverse is true for counterclockwise directions. **c)** Illustration of the apparatus used in the motor planning task, from children's perspective.

**Fig. 2** Percentage of the consistent grips for the overhand and the underhand grips as a function of age (6 vs. 8 years). Error bars indicate the standard error of the between-groups difference (Pfister and Janczyk, 2013).

**Fig. 3** Mean response times (ms) in the motor imagery task (left graph) and in the visual imagery task (right graph) as a function of age (6 vs 8 years) and stimulus rotation (40°, 80°, 120°, 160°). Error bars indicate the standard error of the between-groups difference.

**Fig. 4** Mean response times (ms) in the motor imagery task as a function of age (6 vs. 8 years) and stimulus orientation (medial vs. lateral). Error bars indicate the standard error of the between-groups difference.

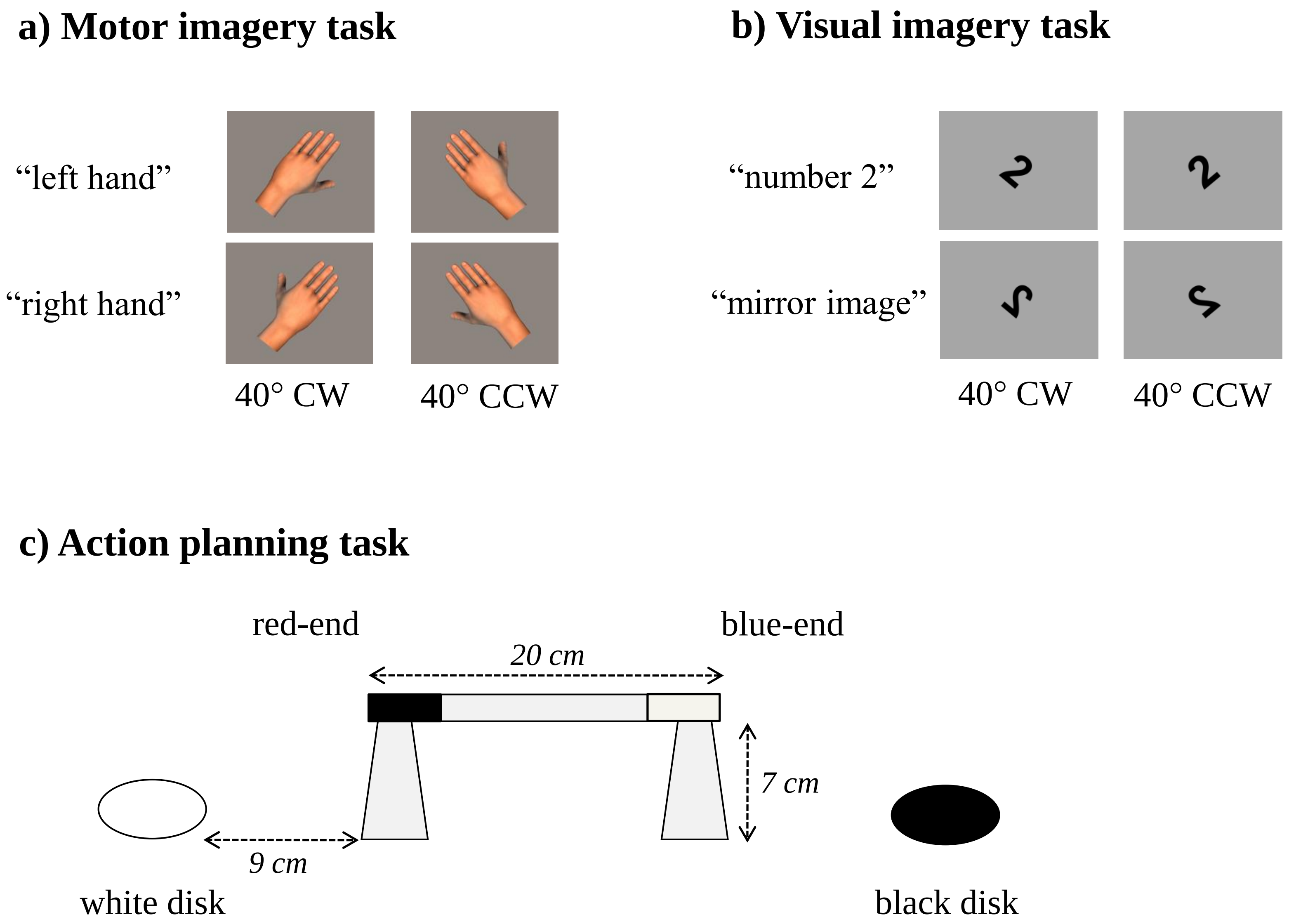
a) Motor imagery task
"left hand"
"right hand"
40° CW
40° CCW
b) Visual imagery task
"number 2"
"mirror image"
40° CW
40° CCW
c) Action planning task
red-end
blue-end
20 cm
7 cm
9 cm
white disk
black disk

Fig1

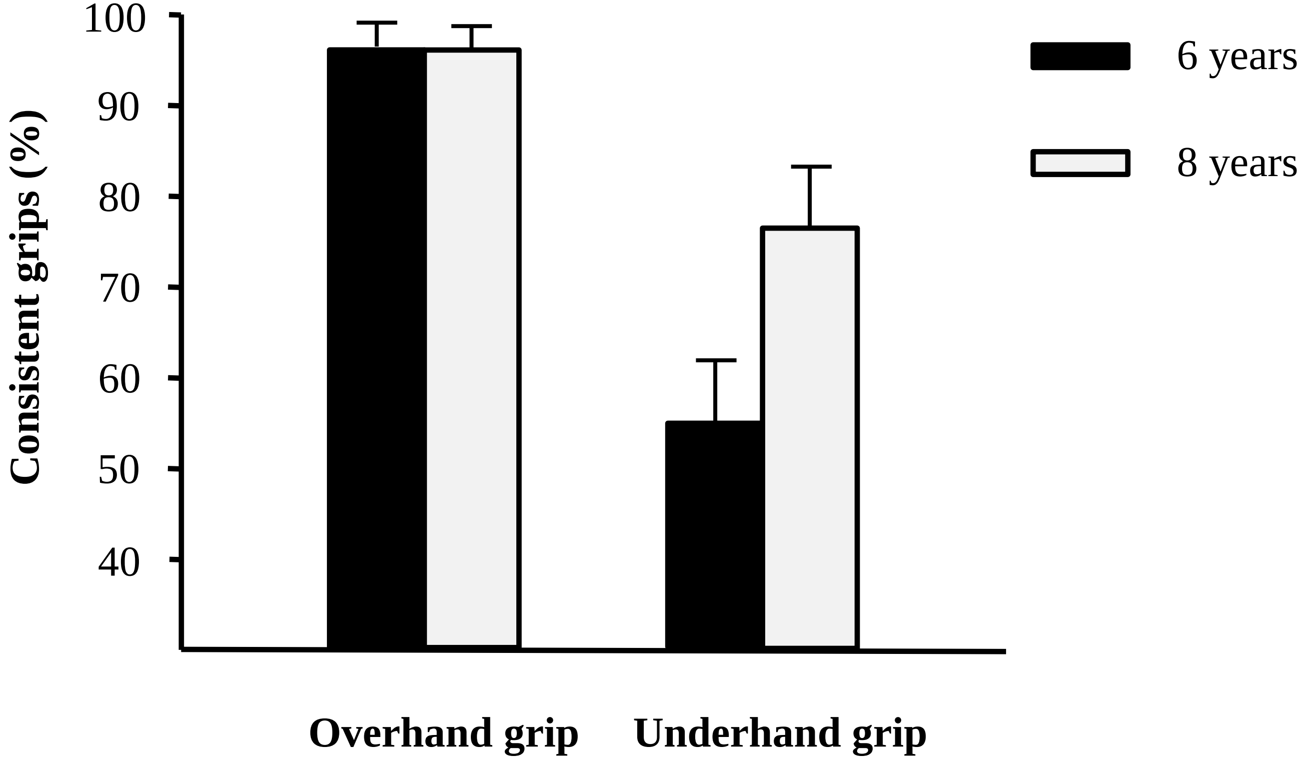
100
90
80
70
60
50
40
Consistent grips (%)
6 years
8 years
Overhand grip
Underhand grip

Fig. 2

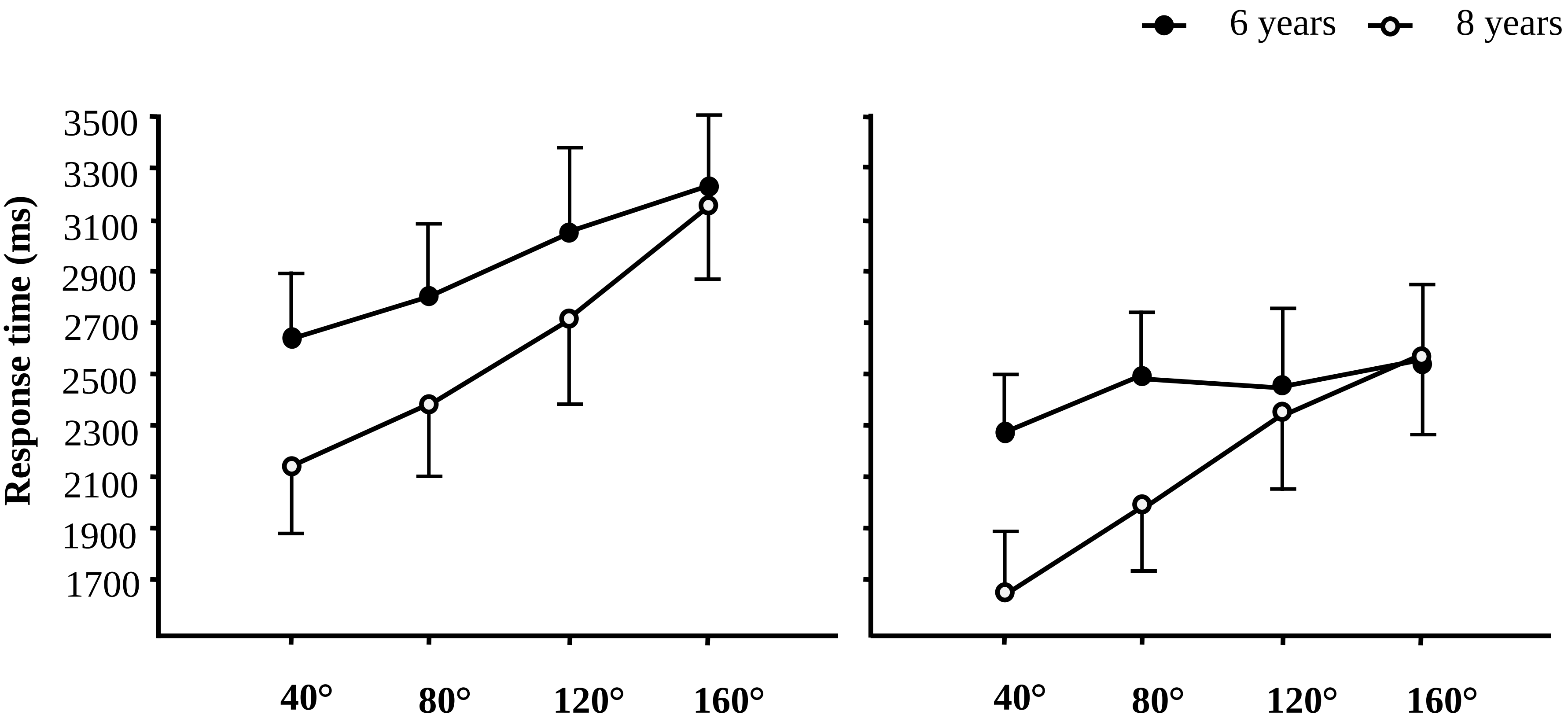
6 years
8 years
Response time (ms)
3500
3300
3100
2900
2700
2500
2300
2100
1900
1700
40°
80°
120°
160°
40°
80°
120°
160°

Fig. 3

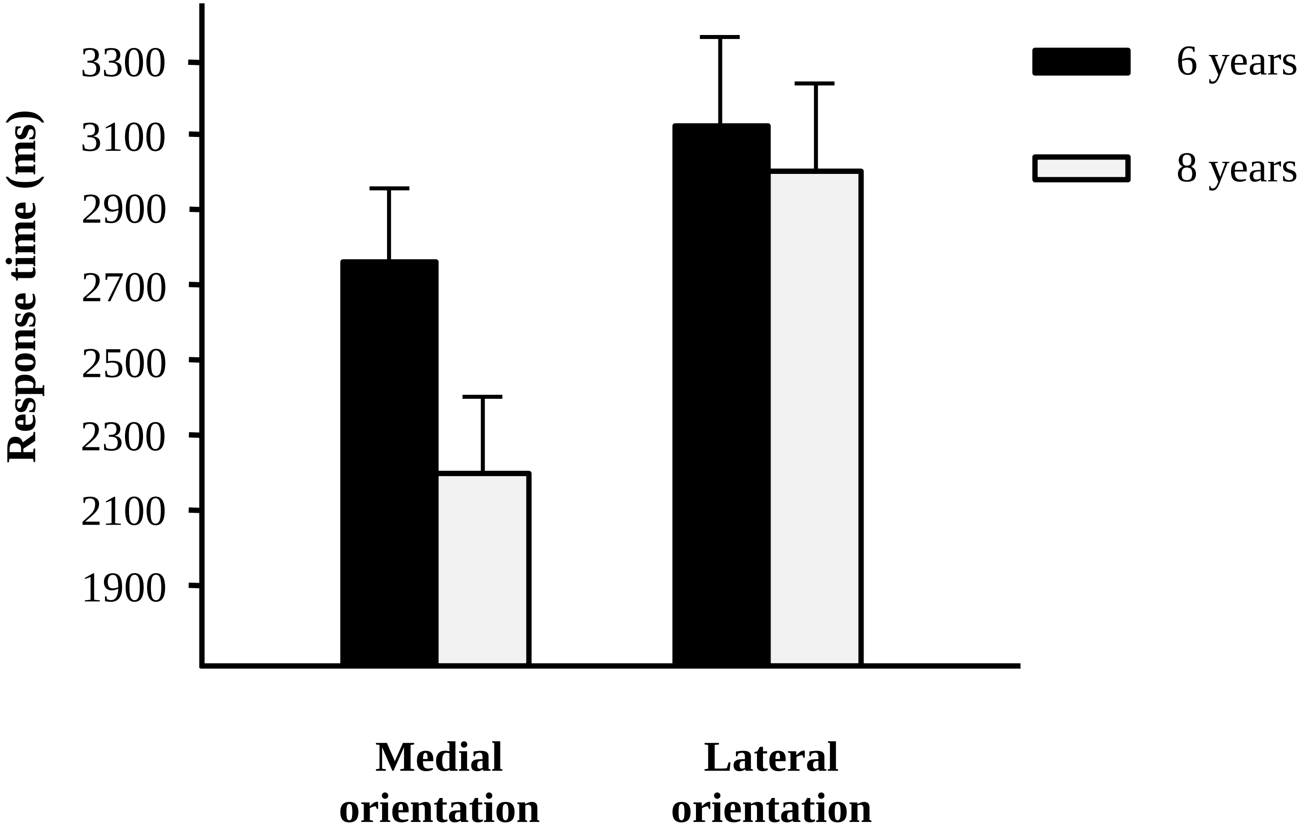
Response time (ms)
3300
3100
2900
2700
2500
2300
2100
1900
6 years
8 years
Medial orientation
Lateral orientation

Fig. 4

| Task by Age groups | Action planning task (underhand grips) | |
|---|---|---|
| *Motor imagery task* | | |
| 6 years | .42 | (*p* < .02) |
| 8 years | .30 | (*p* = .095) |
| *Visual imagery task* | | |
| 6 years | .07 | (*p* = .70) |
| 8 years | -.18 | (*p* = .32) |

Table 1