A Comparison of Motor Imagery Performance in Children with Spastic Hemiplegia and Developmental Coordination Disorder

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Short title: Motor imagery in CP and DCD.

Abstract

Individuals with hemiplegia have difficulty planning movements, which may stem from deficits in motor imagery ability. We explored motor imagery ability in three groups of 21 children, aged 8-12 years: children with hemiplegia; with Developmental Coordination Disorder (DCD); and a comparison group. They completed two tasks requiring laterality judgements of body parts - hand and whole-body rotation. Accuracy in both was reduced for the motor-impaired groups and response time was atypical for the whole-body task. This suggests motor imagery deficits exist in children with hemiplegia and DCD, supporting previous findings that planning deficits in hemiplegia may result from deficits in motor imagery.

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Spastic hemiplegia is a condition characterised by muscle spasticity on one side of the body that affects motor skill execution (Miller, 2005). It can occur as a congenital condition (considered a form of cerebral palsy), or later in life following a stroke or other medical condition affecting the central nervous system. The hemiplegia occurs on the opposite side of the body to the cerebral hemisphere that has suffered damage and severity can vary significantly between individuals – some may experience greater impairment to either their upper or lower limb, while others may experience significant impairment to both. Commonly, individuals with spastic hemiplegia experience difficulty with gait, balance and fine motor skills. Children are also likely to experience significant delays in achieving developmental milestones and have difficulty performing motor skills at an age-appropriate level.

Children with Developmental Coordination Disorder (DCD) also experience difficulty acquiring and performing motor skills at an age-appropriate level. DCD is thought to occur in 5-10% of children and presents as a marked impairment in motor skills that interferes significantly with activities of daily living and/or education (APA, 1994). Children with DCD are clumsy and have difficulties with writing, tying shoelaces, walking, running and jumping. DCD is not associated with any known neurological condition and its aetiology currently remains unexplained. However, a series of papers have provided evidence that suggests a deficit in the ability to utilise motor imagery effectively may underlie some of the motor impairment difficulties observed in children with this diagnosis (Deconinck, Spitaels, Fias, & Lenoir, 2009; Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson et al., 2004; Wilson, Maruff, Ives, & Currie, 2001). Interestingly, a recent line of research has also begun examining whether motor imagery deficits may also be apparent in adolescents with hemiplegia, with these deficits adding to their already obvious motor execution difficulties (Mutsaarts, Steenbergen, & Bekkering, 2007; Steenbergen, van Nimwegen, & Crajé, 2007).

Motor imagery (MI) refers to the mental simulation of a motor act without any overt motor execution (Decety, 1996). It is thought to be a copy of a movement plan coming to consciousness because actual movement has been inhibited (Crammond, 1997) and may be used to predict the outcome of a particular movement. The ability to predict the outcome of movements is considered to be a crucial part of movement planning and also in the ability to accurately utilise internal models of motor control (Blakemore, Wolpert, & Frith, 2002; Flanagan, Vetter, Johansson, & Wolpert, 2003). Forward internal models use a copy of the motor command to predict the outcome of the command. This predicted state is compared to the actual state of the body as the motor command unfolds – external factors may produce differences in the actual outcome when compared to the predicted outcome and these differences can be provided as feedback to update the model, and command, the next time the movement is required (Wolpert, 1997). Hence, internal models provide stability to motor systems, by predicting the outcome of movements before slow, sensori-motor feedback becomes available and are important for smooth, accurate movement. A deficit in the ability to utilise such models may result in slow, poorly coordinated movements, such as those observed in both hemiplegia and DCD.

MI is studied through a number of behavioural paradigms, which have been widely used in adult populations and more often, are now being employed in paediatric samples. Such paradigms include tasks that require individuals to both perform, and imagine performing, a given movement, as well as the mental rotation of body parts. Researchers note that in samples of typical adults, imagined movements are constrained by the same physical and biomechanical limits as actual movements. For example, speed-accuracy trade-offs are observed in imagined movements as they are in physical ones and physically awkward movements take longer to imagine than physically simple movements (e.g. Parsons, 1994; Sirigu et al., 1996). It has also been demonstrated that some adult populations perform atypically on these tasks - for example, patients with posterior parietal lesions (Sirigu, Daprati, Pradat-Diehl, Franck, & Jeannerod, 1999; Sirigu et al., 1996), Parkinson's Disease (Amick, Schendan, Ganis, & Cronin-Golomb, 2006) and apraxia (Tomasino, Rumiati, & Umiltá, 2003).

Interestingly, while it has repeatedly been shown that typically developing children are constrained by the same speed-accuracy trade-offs and biomechanical constraints during MI tasks as adults (e.g. Caeyenberghs, van Roon, Swinnen, & Smits-Engelsman, 2009; Deconinck et al., 2009), this is not the case for children with DCD. The speed-accuracy trade-offs observed in the actual movements of children with DCD are not present when they imagine performing those same movements (Maruff et al., 1999; Wilson et al., 2001), and they are less accurate than their peers when performing imagined hand and whole-body rotations (Williams et al., 2006; Williams et al., 2008). This apparent MI deficit indicates that children with DCD have difficulty simulating movements internally which likely hampers their ability to predict the outcome of a selected movement plan, with movement planning and internal modelling ability thereby reduced. This is supported by findings that MI training can improve the motor skills of children with DCD (Wilson, Thomas, & Maruff, 2002).

It was recently suggested that children with hemiplegia may similarly benefit from MI training (Steenbergen, Crajé, Nilsen, & Gordon, 2009). This stems from research that has demonstrated that adolescents with hemiplegia do not plan complex movements in the same way as their typically developing peers, choosing to grasp objects in such a way that allowed postural comfort at the start of a movement but that do not allow end-state comfort (Mutsaarts, Steenbergen, & Bekkering, 2005, 2006; Steenbergen, Meulenbroek, & Rosenbaum, 2004). This lack of planning was argued to add to the motor execution problems inherent in hemiplegia, thereby worsening their motor skill impairment.

Following the suggestion of Mutsaarts, et al. (2006) that a MI deficit could explain the reduced motor planning skills of adolescents with hemiplegia, two studies were conducted to examine MI ability in this population. The two studies both utilised variations of the hand rotation task, with participants required to make left/right decisions about hands presented on a computer screen at varying angular orientations (Mutsaarts et al., 2007; Steenbergen et al., 2007). These tasks have been shown to elicit use of MI as participants imagine their own hand in the position of the presented hand before making their judgement (de Lange, Hagoort, & Toni, 2005; de Lange, Helmich, & Toni, 2006; Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Thayer & Johnson, 2006; Thayer, Johnson, Corballis, & Hamm, 2001). In the case of hemiplegia, results have been inconsistent. The initial study by Mutsaarts et al. (2007), presented participants with pictures of hands (either closed fist or holding a hammer), and found adolescents with left hemiplegia and controls showed a typical response time (RT) pattern. The right hemiplegia group showed no significant trade-off in RT, indicating their responses were not obeying the biomechanical limitations of the imagined movements. There was no difference in total accuracy among the groups, (despite the two hemiplegia groups making twice as many errors as the controls), however, the left hemiplegia group made significantly more errors when responding to left than to right hands. This laterality effect was not observed in the other groups. The authors concluded that the left hemiplegia group were utilising MI effectively, as they showed the typical RT trade-off and a laterality effect, which could be indicative of embodied knowledge about the impaired left body-side. In contrast, it was argued the right hemiplegia group were unable to utilise MI and and were instead using an alternative technique, such as using viewpoint-independent cues to make their decision. Such cues might include the location of the thumb, for example. Thus, the authors argued that a MI deficit is present only in adolescents with right hemiplegia, supporting earlier findings that motor planning deficits may be restricted to those with right hemiplegia (Steenbergen et al., 2004).

A follow-up study by Steenbergen et al. (2007) used a similar paradigm and reported no differences in the effect of angular orientation on RT or accuracy between left and right sided hemiplegic participants and healthy controls, though responses were generally slower for the hemiplegic groups. The authors argued that participants in the second study were not using MI and were perhaps instead using a visual imagery approach. In this context, visual imagery refers to treating the hands as objects, rather than body parts, and imagining them rotating from an external perspective, rather than imagining one’s own hand moving into the position of the stimulus. While the mental rotation of hands has been reported to activate the motor system, including the primary motor cortex, the premotor cortex and the posterior parietal lobe, the rotation of objects does not and instead activates the inferior and superior parietal lobes bilaterally (Kosslyn et al., 1998). Given that Steenbergen et al. specifically utilised an experimental set-up that facilitated the use of MI through postural congruence (de Lange et al., 2006), it is interesting that they argue that MI was not used. Why these adolescents would apparently utilise a non-motor strategy, if indeed they did, in a task that has been designed to facilitate its use and at an age at which MI ability should have clearly emerged (Choudhury, 2007; Choudhury, Charman, Bird, & Blakemore, 2007) is unclear. An alternative argument may be that presenting the task with postural congruence made it easier to complete than the task in the previous study and that the hemiplegia groups did use MI and, while slower at performing the task, were able to achieve levels of accuracy equivalent to their peers.

Before implementing MI training for children with hemiplegia, it is vital that we gain a better understanding of the MI ability of this population as the conflicting studies described above have been conducted with adolescents, whose MI ability may differ from younger children. Therefore, the aim of the current study was to explore the MI ability of children with hemiplegia, whilst comparing them to children with DCD and their typically developing peers. Children with DCD provide a good reference point for comparison given their documented deficits in MI ability (Deconinck et al., 2009; Williams et al., 2006; Williams et al., 2008; Wilson et al., 2004; Wilson et al., 2001). They also demonstrate improved motor skills following MI training (Wilson et al., 2002). If children with hemiplegia display a similar pattern of impairment to those with DCD, this would support the proposition that motor planning deficits in hemiplegia are linked to deficits in action representations (or MI) (Mutsaarts et al., 2007) and that MI training may be of benefit.

This study will further build on previous work by examining responses to hand stimuli presented in clockwise and counter-clockwise directions to determine whether MI is being employed. If participants engage in MI, responses to left hands in counter-clockwise directions should take longer than to those in clockwise directions due to the biomechanical constraints of movement – i.e. it is harder to imagine a left hand at 225° of rotation than at 135° (de Lange et al., 2006). Additionally, the study includes a more complex measure of MI – a whole-body task requiring more difficult imagined transformations of the whole body around vertical and horizontal axes. Such transformations allow individuals to take on the perspective of other people (Zacks, Mires, Tversky, & Hazeltine, 2002), an important component of motor learning through modelling. Our previous studies have demonstrated that the complexity of this task also means we are less likely to find ceiling effects in terms of accuracy, providing more detailed information regarding possible MI deficits (Williams et al., 2006; Williams et al., 2008). We expected the hemiplegia and DCD groups to show similar performance deficits in MI tasks, when compared to a typically developing comparison group. We further expected that these deficits would be more evident in the whole-body transformation task, which is more complex and less likely to produce ceiling effects in our comparison group.

Method

Participants

Twenty-one children (10 males) with mild spastic hemiplegia were recruited for this study with the assistance of the Victorian Cerebral Palsy Register, from a potential pool of 98 children who were aged 8-13 years, were independently mobile with a Gross Motor Function Score of I or II and were free of visual, hearing or intellectual impairment. The mean age was 10y 4m (SD = 1y 6m) and 11 children had right-sided hemiplegia. All of these children had an estimated IQ >70, with a mean of 101.05 (SD = 11.1, range 84-122) using the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) and were attending regular primary schools.

The DCD and comparison groups, described previously (Williams et al., 2008), were recruited using a previously validated method (Wilson, Maruff, &

McKenzie, 1997). Primary school teachers were asked to identify children whose motor skills they believed to be below age-expected levels and which interfered with academic or everyday activities. Children were then assessed on the Movement ABC (Henderson & Sugden, 1992) and were considered to have DCD if they performed below the 5th percentile and no documented neurological or physical pathology (e.g. cerebral palsy, muscular dystrophy) was reported by the school or parents. Teachers also identified children with typical motor ability to form the comparison group. These children were also assessed on the Movement ABC and were included if they performed above the 20th percentile.

The 21 children in the DCD group (9 males) had a mean age of 9y 5m (SD = 8m), while the 21 children (9 males) in the comparison group had a mean age of 9y 5m (SD = 1y 4m). IQ estimates were not available for children in the DCD and comparison groups.

Procedure

Study methods were approved by the relevant institutional ethics committees. All children were assessed by Dr Williams or a trained research assistant who were aware of which children were in the hemiplegia group, but were unaware of whether a child was suspected of having DCD or not. Children with hemiplegia were assessed at the Royal Children’s Hospital, Melbourne, or at school. Children in the DCD and comparison groups were assessed at school. Two mental rotation tasks eliciting MI were presented using E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA). Stimuli were high resolution images of either hands (left-right) or a man facing the participant with his arm (left-right) outstretched (Figure 1), centred on a computer screen. Hand stimuli measured 9 cm by 8 cm and whole-body stimuli measured 9 cm by 6 cm. Stimuli were presented in 45° increments between 0º and 360º, with the stimuli remaining on the screen for up to 10 s. Responses were recorded to the nearest 1ms.

Participants sat in front of the computer screen and were required to press two allocated keys (designated left and right) in response to the stimuli. Five practice trials were provided, followed by 40 test trials, each followed by a random delay of between 2 and 3 s. If participants did not respond to a stimulus within 10 s, the stimulus disappeared and the next trial began.

For the hand task, participants were instructed to imagine their own hand in the position of the stimulus, using this as a guide to decide whether the hand was left or right. In the whole-body task, participants were asked to determine whether the stimulus man was holding out his left or right arm. They were instructed to imagine themselves in the position of the man to help them decide which arm was being held out. In both tasks, children were asked to respond as quickly and accurately as possible. Presentation of tasks was counterbalanced across participants.

Data Analysis

Data that had the same angle of rotation from 0º, regardless of direction, were combined (e.g. 45º and 315º were combined with both 45º from upright). This commonly used technique in mental rotation increases reliability of estimates by increasing the number of trials at each angle (see, for example, Harris et al., 2000; Roelofs, van Galen, Keijsers, & Hoogduin, 2002). This resulted in eight trials at each of 5 angles (0°, 45°, 90°, 135° and 180°), with an equal number of left and right hands/arms, randomly presented at each angle for each participant.

For each participant, mean RTs were calculated for each angle, following which anticipatory responses were removed (<250ms). For the hand task, 0.2%, 0.8% and 1.1% of trials were removed for the comparison, DCD and hemiplegia groups respectively. For the whole body task, 1.7%, 4.1% and 5.1% of trials were removed for the comparison, DCD and hemiplegia groups respectively. Mean RT was then recalculated for each angle. Group RT data were submitted to a 5 (angle) x 3 (group) ANOVA with repeated measures on the first factor for both tasks, with multivariate tests conducted to protect against violations to the assumption of sphericity. Significant findings were followed up using pairwise comparisons of estimated marginal means with Bonferroni adjusted alpha levels.

To determine whether RT was constrained by biomechanical limitations in the hand task, mean RTs for left and right hands separately in clockwise (CW) and counter-clockwise (CCW) directions were determined. For each participant, mean RTs for left and right hands were calculated at the following combinations of angles - 45°, 90° and 135° (CW) and 225°, 270° and 315° (CCW). This data was then submitted to a 2 (laterality) x 2 (rotation direction) x 3 (group) ANOVA with repeated measures on the first two factors. Significant findings were followed up using pairwise comparisons of estimated marginal means with Bonferroni adjusted alpha levels. This analysis was not conducted with the whole-body task as a relationship between the laterality of the stimulus and the direction of rotation is not expected in whole-body rotations (see for example, Zacks, Ollinger, Sheridan, & Tversky, 2002).

Consistent with Mutsaarts (Mutsaarts et al., 2007) and Steenbergen (Steenbergen et al., 2007), accuracy was averaged across angles for both tasks to create an overall accuracy figure. Mean accuracy for each task was then submitted to a univariate ANOVA, with significant group effects followed by post-hoc testing using Tukey's HSD.

Results

A one-way ANOVA found a significant difference in mean age among the groups, *F*(2,60) = 4.30, *p* = .018. Post-hoc tests using Tukey's HSD demonstrated that the hemiplegia group were significantly older than both the DCD (*p* = .036) and comparison (*p* = .036) groups. As a result, we added age as a covariate to our imagery analyses.

Initial analysis was conducted to examine whether side of hemiplegia (left, right) had an effect on the tasks presented for the hemiplegia group. Repeated measures ANOVA on mean RT and accuracy for the hand and whole-body tasks revealed no significant interaction between side of hemiplegia and angle (*p* > .05). There was also no significant main effect for side of hemiplegia in all the conditions (*p* > .05).

Hand task

Results showed that age covaried significantly with RT on the hand task, *F*(1,59) = 4.32, *p* = .042. After partialling out the variance associated with age, repeated measures ANOVA on mean RT did not reveal a significant interaction between group and angle (*p* > .05). There was a significant main effect for angle (see Figure 2), Wilks' $\Lambda = .82$, *F*(4,56) = 2.99, *p* = .026, $\eta^2 = .18$, and a significant effect for group, *F*(2,59) = 3.24, *p* = .046, $\eta^2 = .10$. Further examination of the main effect for group revealed the hemiplegia group were significantly slower to respond than the comparison group (*p* = .045). No other group comparisons were statistically significant.

Repeated measures ANOVA on mean RT to examine the interaction between stimulus laterality, rotation direction and group (see Figure 3) revealed only one significant interaction, between laterality and direction of rotation, Wilks' $\Lambda = .92$, $F(1,60) = 5.47$, $p = .023$, $\eta^2 = .08$. Planned comparisons revealed that responses to hands presented in the CCW direction were slower when the stimulus was a left hand, compared to a right hand ($p = .004$). There was also a small trend towards faster responses in the CCW direction compared to the CW direction for right hands, though this failed to reach significance ($p = .07$).

Age did not covary significantly with mean accuracy, $F(1,59) = 3.15$, $p = .081$, $\eta^2 = .051$, and so was removed from the analysis. Mean accuracy for each group was 81.0% for the DCD group, 79.6% for the hemiplegia group and 95.7% for the the comparison group (see Figure 2). ANOVA revealed a significant effect for group, $F(2,60) = 6.10$, $p = .004$, $\eta^2 = .17$, with both the hemiplegia and the DCD groups significantly less accurate than the comparison group (*p* = .007 and .015 respectively). The hemiplegia and DCD groups did not differ.

Whole-body task

Age did not covary significantly with mean RT on the whole-body task, $F(1,56) = 0.12$, $p = .73$, $\eta^2 = .002$, and so was removed from the analysis. There was a significant interaction between angle and group, Wilks' $\Lambda = .73$, $F(8,108) = 2.32$, $p = .024$, $\eta^2 = .15$, (see Figure 4). The effect for angle was significant for the hemiplegia (Wilks' $\Lambda = .84$, $F(4, 54) = 7.75$, $p < .001$, $\eta^2 = .37$) and DCD groups (Wilks' $\Lambda = .841$, $F(4, 54) = 2.55$, $p = .050$, $\eta^2 = .159$), but not for the comparison group ($p = .89$).

Simple main effects for group were only significant at 0º, $F(2, 57) = 5.81$, $p = .005$, $\eta^2 = .169$, where the hemiplegia ($p = .026$) and DCD ($p = .009$) groups were significantly faster to respond than the comparison group .

Age did not covary significantly with mean accuracy, $F(1,56) = 3.77$, $p = .057$, $\eta^2 = .063$, and so was removed from the analysis. Mean accuracy for each group was 49.0% for the DCD group, 56.3% for the hemiplegia group and 85.0% for the the comparison group (see Figure 4). ANOVA revealed a significant effect for group, $F(2,57) = 13.10$, $p < .001$, $\eta^2 = .32$, with both the hemiplegia and the DCD groups significantly less accurate than the comparison group ($p = .001$ and $< .001$ respectively). The hemiplegia and DCD groups did not differ.

Discussion

This study aimed to explore the performance patterns of children with DCD and hemiplegia on two tasks eliciting the use of MI. Our hypotheses were generally supported, with no significant differences between these two groups of children with motor impairment, though both were significantly less accurate than a group of healthy peers. We discuss the findings for each task individually below.

Hand task No differences were identified between children with left and right hemiplegia in performance (RT or accuracy) on the hand task, supporting the findings of Steenbergen et al. (2007). For subsequent analyses, we compared the hemiplegia group as a whole to the DCD and comparison groups. Also in keeping with Steenbergen and colleagues, the hemiplegia group in the current study was significantly slower than the comparison group in responding to the hand stimuli. The

DCD group did not differ significantly in RT from either the comparison or hemiplegia groups.

In contrast to previous studies conducted with young adults with hemiplegia, we identified significantly reduced accuracy in the hemiplegia group compared with the comparison group. Indeed, the hemiplegia and DCD groups displayed similar levels of accuracy (approximately 80%), with the DCD group also significantly less accurate than the comparison group. Hence, the DCD group performed similarly to the comparison group in regard to RT, but were impaired in their accuracy of left-right judgements. The hemiplegia group was also less accurate than the comparison group, but were, in addition, significantly slower in their responses. These findings relating to accuracy in the hand task are particularly important, because inaccurate performance likely signifies greater deficits than slow, but accurate performances.

The hand task in this study was administered in a way that would be expected to facilitate the use of MI – we presented hand stimuli in the back view, creating postural congruency between the subject's own hands and those displayed, which we would expect to increase the reliance on motor imagery (Sirigu & Duhamel, 2001) and we provided clear motor imagery instructions. Both the effect of angle on RT and the comparison of RTs and accuracy to left and right stimuli in CW and CCW directions support the use of MI in all three groups. Figure 3 shows the mean RTs for each group were consistent with the biomechanical constraints of the task – i.e. RTs were slower to left hand stimuli presented in a CCW direction compared to a CW direction, with the opposite being true for right hand stimuli (with the exception of the DCD group, whose responses to right hand stimuli was not notably different in either direction). This was further supported statistically, with CCW responses significantly slower for left hands compared to right. We argue then that MI was employed by all three groups when completing the hand task and that children with hemiplegia are significantly impaired in the ability to use MI, with responses that are significantly slower and less accurate than their typically developing peers. Children with DCD are similarly impaired in terms of accuracy, though they do not experience the same slowing of responses experienced by the children with hemiplegia.

Whole-body task Before discussing the whole-body task, it is important to note that typical response patterns on this task differ from most mental rotation paradigms. This is because a change in one's (egocentric) perspective is generally made, rather than a rotation of a body part to match a stimulus (Zacks, Gilliam, & Ojemann, 2003; Zacks, Mires et al., 2002; Zacks, Ollinger et al., 2002). This transformation is easier to make when the stimulus is presented at 180° of rotation as the participant no longer needs to perform an imagined transformation around the vertical axis of the body (i.e. imagine turning around to face in the opposite direction) - they need only to perform an imagined rotation around the horizontal axis (i.e. imagine kicking their legs up in the air). Thus, little trade-off for angle occurs in the whole-body task and indeed, accuracy can sometimes increase slightly with increases in angle (Zacks, Ollinger et al., 2002; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999).

Keeping in mind the different typical response pattern for this task, the results showed that the comparison group displayed typical response patterns, whereas RT for the DCD and hemiplegia groups was atypical. Both of the latter groups showed significant effects for angle, suggesting that they were actually attempting to rotate the stimulus to the upright position, rather than performing an egocentric transformation. Doing so would then require the individual to maintain a representation of this rotated stimulus in their mind while they performed an imagined transformation of either themselves, or the stimulus, around the vertical axis of the body. The difficulty of doing so may have contributed to reduced accuracy. Of note RTs at 0° were quite low for the DCD and hemiplegia groups, indicating that the transformation around the vertical axis may have been too demanding, potentially resulting in either rushed responses or guessed answers, after performing the rotation to the upright. We have previously suggested that this might be the case for the children with DCD (Williams et al., 2008) and the suggestion is supported by the high error rate and increased number of anticipatory responses observed in both the DCD and hemiplegia groups for the whole body task – more than double the number observed in the comparison group and almost two thirds of which occurred when the stimulus was presented at lower angles (0-90°).

As with the hand task, it is important to consider what techniques may have been implemented by each group to complete the task. Unfortunately, the laterality effect in CW and CCW directions present in the hand task is not present in the whole-body task, making it difficult to determine the technique used. We believe that the comparison group was using MI, given that their pattern of response has been reported as unique to this task, and closely matches that previously observed in adult populations and under fMRI conditions (Zacks, Ollinger et al., 2002; Zacks et al., 1999). In contrast, it appears that neither the hemiplegia or DCD group were fully complying with the MI instructions but were trying to rotate the stimulus to the upright position before responding. They may have been able to do so by treating the stimulus as an object, rather than viewing it as a body (i.e. using visual imagery) – such a technique has been reported previously when two whole-body stimuli are presented and a same/different decision, rather than one of laterality, was required (Zacks, Ollinger et al., 2002). While whole-body rotations result in significant activation at the parietal-temporal-occipital junction, treating whole-body stimuli as objects results in significant increases in right hemisphere activation. The use of a technique other than that instructed and generally elicited by the task suggests that a deficit in the ability to perform MI accurately may lead to the use of other strategies for performing the task, even if those strategies are unsuccessful.

General Discussion Our results indicate that both the hemiplegia and DCD groups were impaired in their ability to perform both the hand and whole-body (imaging) tasks as accurately as their typically developing peers. This is in contrast to previous studies with young adults with hemiplegia, where no difference in accuracy from comparison groups have been observed (Mutsaarts et al., 2007; Steenbergen et al., 2007).

There were few differences in performance between the DCD and hemiplegia groups, suggesting that MI ability may be similarly impaired in both groups. If this is the case, and the suggestion of Mutsaarts and colleagues that there is a link between deficits in MI ability and motor planning deficits (Mutsaarts et al., 2007) is correct, then this supports the likelihood of motor planning deficits in children with DCD, similar to that observed in hemiplegia. It remains unclear whether this impairment is one of the underlying causes of motor skill impairment in children with DCD. Instead, their motor skill impairment may prevent them from accurately forming internal models, which is then reflected in MI impairments. Future research needs to explore this issue as it will have a significant impact on approaches taken to intervention with these children.

A further point of interest was the lack of differences in performance between children with left and right hemiplegia. This finding is in contrast to studies which have shown planning deficits are restricted to individuals with right-sided hemiplegia (i.e. left brain damage) (e.g. Steenbergen et al., 2004) and the study of Mutsaarts and colleagues (2007), which reported atypical RT patterns on a MI task in right-sided hemiplegia, but not left sided. There is support from previous studies for the suggestion that individuals with right-sided hemiplegia only would be impaired in their ability to utilise MI suggesting left hemisphere dominance in MI tasks (Kosslyn et al., 1998; Tomasino, Toraldo, & Rumiati, 2003). It is interesting then that we did not find any differences between children with left and right hemiplegia here. Our use of explicit MI instructions, not used in previous studies, may have decreased the likelihood of techniques other than MI being utilised, thereby highlighting MI deficits not previously observed in children with left-sided hemiplegia. Alternatively, the younger age of participants in our study may have been linked to the MI deficit observed generally in our hemiplegic group – as the children age, those with left-sided hemiplegia may show improvements in their imagery ability which are not experienced by those with right-sided hemiplegia due to the compromised development of the left side of the brain. Some of the discrepancies across studies might also be linked to variance in the location, extent and type of lesion underlying the hemiplegia, something that has not been considered in any of the studies to date. Further research with younger hemiplegic children, across a range of MI and planning tasks, is needed to clarify this issue further. It would also be useful to demonstrate that these MI deficits in hemiplegia are specific to motor imagery and are not linked to a general inability to perform mental rotation tasks. This could be done by examining their performance on a visual imagery task, such as the alphanumeric rotation task that we have previously utilised to demonstrate such specificity in children with DCD (Williams et al., 2006).

As is the case for all studies attempting to measure internal cognitive processes, this study was limited by the fact that our tasks assess MI implicitly. Our results should be treated with some caution as without more direct evidence (e.g. neuroimaging), it is not possible to conclusively state that all children were utilising MI, though the significant laterality effects in the hand task indicate that MI was most likely used by all groups. This inference is based on comparison to typical response patterns observed in neuroimaging studies of the same or similar tasks (e.g. Kosslyn et al., 1998; Zacks et al., 2003). We were also limited in our comparison of left and right-sided hemiplegia, with insufficient data to compare the performance of each group on left and right-sided stimuli. Finally, although we were able to demonstrate that there was no significant intellectual impairment in our hemiplegia group, we did not have IQ estimates for our DCD or comparison groups. As such we cannot conclusively state that IQ did not have an impact on our findings.

In summary, this study found similar performance deficits in tasks that generally elicit the use of MI for children with mild spastic hemiplegia to those previously reported in children with DCD. We argue that these results support a reduced ability to utilise MI and lend support to the suggestion of an underlying motor planning deficit in both groups of children. It is unclear whether this deficit is the result of impaired neural networks or due to motor execution difficulties, but we do know that MI training can improve motor skill execution in children with DCD (Wilson et al., 2002). Given the similarities in performance between the hemiplegia and DCD groups here, MI training, which involves visual modelling, internal and external mental skill rehearsal and overt practice, may also benefit children with hemiplegia, as suggested by Steenbergen et al. (2009). Further investigation in both groups is warranted and is likely to impact significantly on future intervention strategies.

References

Amick, M. M., Schendan, H. E., Ganis, G., & Cronin-Golomb, A. (2006). Frontostriatal circuits are necessary for visuomotor transformation: Mental rotation in Parkinson's disease. *Neuropsychologia, 44*, 339-349.

APA; American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.

Blakemore, S.-J., Wolpert, D. M., & Frith, C. D. (2002). Abnormalities in the awareness of action. *Trends in Cognitive Sciences, 6*, 237-242.

Caeyenberghs, K., van Roon, D., Swinnen, S. P., & Smits-Engelsman, B. C. M. (2009). Deficits in executed and imagined aiming performance in brain-injured children. *Brain and Cognition, 69*, 154-161.

Choudhury, S. (2007). Adolescent development of motor imagery in a visually guided pointing task. *Consciousness and Cognition, 16*, 886-896.

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

Crammond, D. J. (1997). Motor imagery: Never in your wildest dream. *Trends in Neuroscience, 20*, 54-57.

de Lange, F. P., Hagoort, P., & Toni, I. (2005). Neural topography and content of movement representations. *Journal of Cognitive Neuroscience, 17*, 97-112.

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

Decety, J. (1996). The neurophysiological basis of motor imagery. *Behavioural Brain Research, 77*, 45-52.

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

Flanagan, J. R., Vetter, P., Johansson, R. S., & Wolpert, D. M. (2003). Prediction precedes control in motor learning. *Current Biology, 13*, 146-150.

Harris, I. M., Egan, G. F., Sonkkila, C., Tochon-Danguy, H. J., Paxinos, G., & Watson, J. D. G. (2000). Selective right parietal lobe activation during mental rotation. A parametric PET study. *Brain, 123*, 65-73.

Henderson, S. E., & Sugden, D. A. (1992). *Movement Assessment Battery for Children.* London: The Psychological Corporation.

Kosslyn, S. M., Digirolamo, G. J., Thompson, W. L., & Alpert, N. M. (1998). Mental rotation of objects versus hands: Neural mechanisms revealed by positron emission tomography. *Psychophysiology, 35*, 151-161.

Maruff, P., Wilson, P. H., Trebilcock, M., & Currie, J. (1999). Abnormalities of imagined motor sequences in children with developmental coordination disorder. *Neuropsychologia, 37*, 1317-1324.

Miller, F. (2005). *Cerebral Palsy*. New York: Springer Science + Business Media Inc.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2005). Anticipatory planning of movement sequences in hemiparetic cerebral palsy. *Motor Control, 9*, 439-458.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2006). Anticipatory planning deficits and context effects in hemiparetic cerebral palsy. *Experimental Brain Research, 172*, 151-162.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2007). Impaired motor imagery in right hemiparetic cerebral palsy. *Neuropsychologia, 45*, 853-859.

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

Roelofs, K., van Galen, G. P., Keijsers, G. P. J., & Hoogduin, C. A. L. (2002). Motor initiation and execution in patients with conversion paralysis. *Acta Psychologia, 110*, 21-34.

Sirigu, A., Daprati, E., Pradat-Diehl, P., Franck, N., & Jeannerod, M. (1999). Perception of self-generated movement following left parietal lesion. *Brain, 122*, 1867-1874.

Sirigu, A., & Duhamel, J. R. (2001). Motor and visual imagery as two complementary but neurally dissociable mental processes. *Journal of Cognitive Neuroscience, 13*, 910-919.

Sirigu, A., Duhamel, J. R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental representation of hand movements after parietal cortex damage. *Science, 273*, 1564-1568.

Steenbergen, B., Crajé, C., Nilsen, D. M., & Gordon, A. M. (2009). Motor imagery training in hemiplegic cerebral palsy: A potentially useful therapeutic tool for rehabilitation. *Developmental Medicine and Child Neurology, 51*, 690-696.

Steenbergen, B., Meulenbroek, R. G. J., & Rosenbaum, D. A. (2004). Constraints on grip selection in hemiparetic cerebral palsy: effects of lesional side, end-point accuracy, and context. *Cognitive Brain Research, 19*, 145-159.

Steenbergen, B., van Nimwegen, M., & Crajé, C. (2007). Solving a mental rotation task in congenital hemiparesis: Motor imagery versus visual imagery. *Neuropsychologia, 45*, 3324-3328.

Thayer, Z. C., & Johnson, B. W. (2006). Cerebral processes during visuo-motor imagery of hands. *Psychophysiology, 43*, 401-412.

Thayer, Z. C., Johnson, B. W., Corballis, M. C., & Hamm, J. P. (2001). Perceptual and motor mechanisms for mental rotation of human hands. *Neuro Report, 12*, 3433-3437.

Tomasino, B., Rumiati, R. I., & Umiltá, C. A. (2003). Selective deficit of motor imagery as tapped by a left-right decision of visually presented hands. *Brain and Cognition, in press*.

Tomasino, B., Toraldo, A., & Rumiati, R. I. (2003). Dissociation between the mental rotation of visual images and motor images in unilateral brain-damaged patients. *Brain and Cognition, 51*, 368-371.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence Manual*. San Antonia, TX: Harcourt Assessment, Inc.

Williams, J., Thomas, P. R., Maruff, P., Butson, M., & Wilson, P. H. (2006). Motor, visual and egocentric transformations in children with developmental co-ordination disorder. *Child: Care, Health and Development, 32*, 633-647.

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

Wilson, P. H., Maruff, P., Butson, M., Williams, J., Lum, J., & Thomas, P. R. (2004). Internal representation of movement in children with developmental coordination disorder: A mental rotation task. *Developmental Medicine & Child Neurology, 46*, 754-759.

Wilson, P. H., Maruff, P., Ives, S., & Currie, J. (2001). Abnormalities of motor and praxis imagery in children with DCD. *Human Movement Science, 20*, 135-159.

Wilson, P. H., Maruff, P., & McKenzie, B. E. (1997). Covert orienting of visuospatial attention in children with developmental coordination disorder. *Developmental Medicine & Child Neurology, 39*, 736-745.

Wilson, P. H., Thomas, P. R., & Maruff, P. (2002). Motor imagery training ameliorates motor clumsiness in children. *Child Neurology, 17*, 491-498.

Wolpert, D. M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences, 1*, 209-216.

Zacks, J. M., Gilliam, F., & Ojemann, J. G. (2003). Selective disturbance of mental rotation by cortical stimulation. *Neuropsychologia, 41*, 1659-1667.

Zacks, J. M., Mires, J., Tversky, B., & Hazeltine, E. (2002). Mental spatial transformations of objects and perspective. *Spatial Cognition and Computation, 2*, 315-322.

Zacks, J. M., Ollinger, J. M., Sheridan, M. A., & Tversky, B. (2002). A parametric study of mental spatial transformations of bodies. *NeuroImage, 16*, 857-872.

Zacks, J. M., Rypma, B., Gabrieli, J. D. E., Tversky, B., & Glover, G. H. (1999). Imagined transformation of bodies: An fMRI investigation. *Neuropsychologia, 37*, 1029-1040.

Figure 1. Task stimuli. (a) Hand stimulus (left hand, 135° of rotation); (b) Whole-body stimulus (left arm out, 45°).

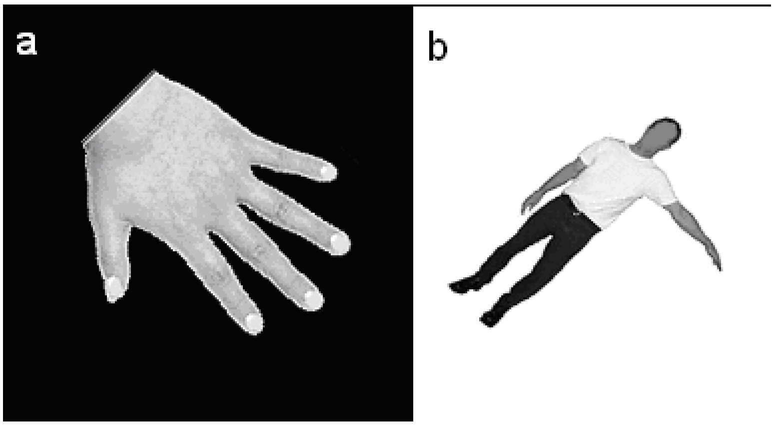

Figure 2. Hand task – (a) mean response time (ms) by angle (degrees) and (b) total mean accuracy.

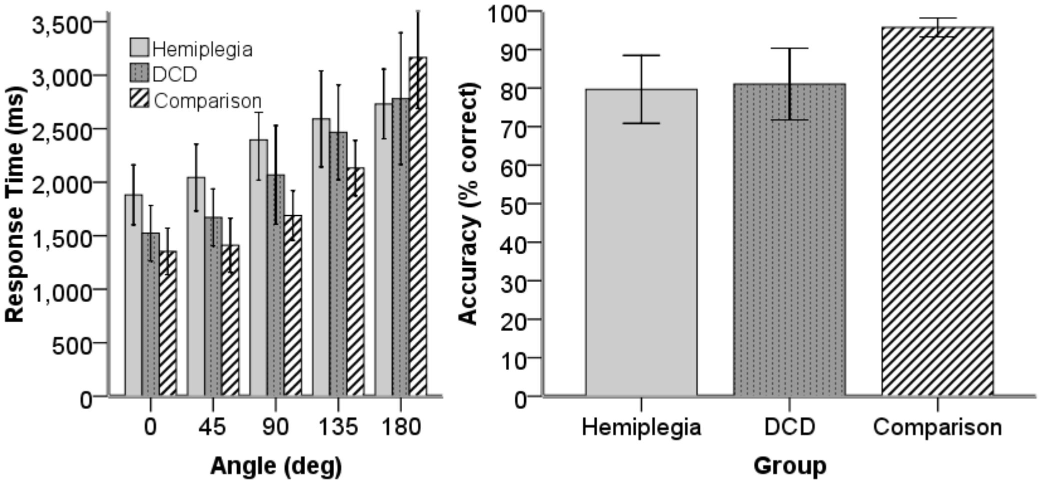

Figure 3. Laterality effect. Mean response time to left and right stimuli in clockwise (CW) and counter-clockwise (CCW) directions for each group.

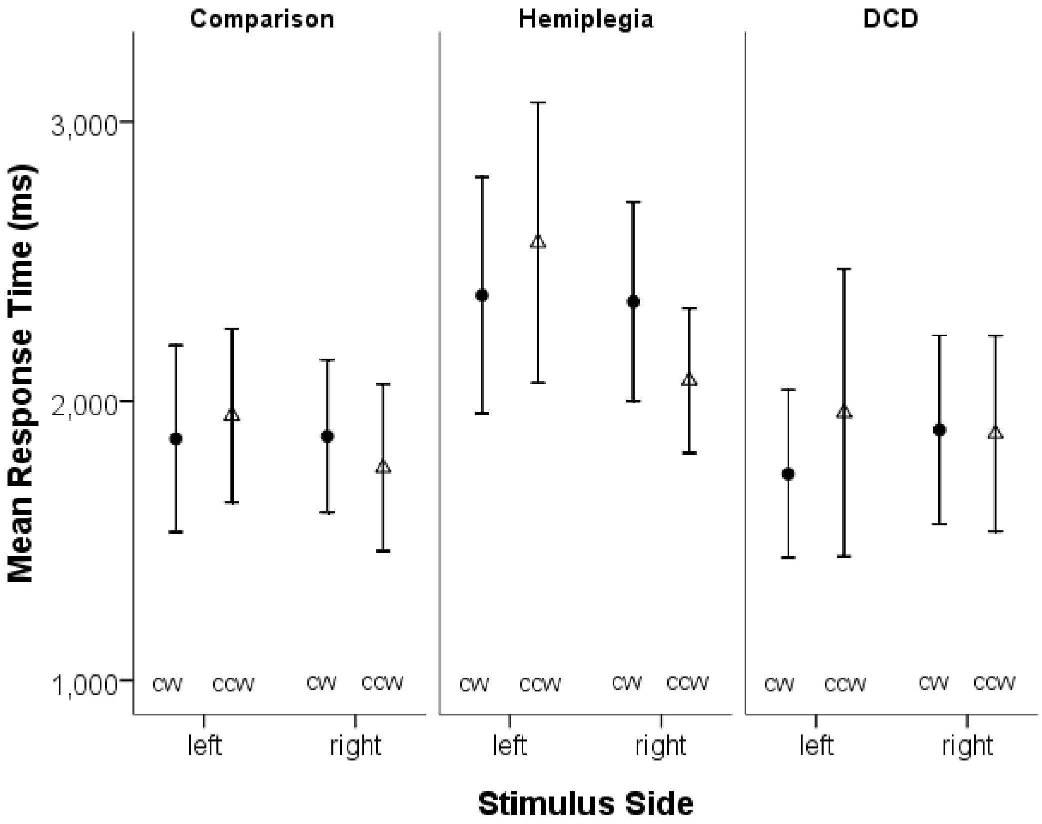

Figure 4. Whole-body task – (a) mean response time (ms) by angle (degrees) and (b) total mean accuracy.