NEUROPSYCHOLOGIA

Neuropsychologia 45 (2007) 853–859

www.elsevier.com/locate/neuropsychologia

Impaired motor imagery in right hemiparetic cerebral palsy

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Received 18 January 2006; received in revised form 14 August 2006; accepted 19 August 2006

Abstract

It is generally assumed that movements of a part of the body (e.g., hands) are simulated in motor imagery (MI) tasks. This is evidenced by a linear increase in reaction time as a function of the angular rotation of the stimulus. Under the assumption that MI plays a critical role for anticipatory motor planning, which is known to be impaired in individuals with right hemiparetic cerebral palsy (right HCP; left congenital brain damage), but to a lesser extent in individuals with left HCP, we hypothesized that MI is impaired in the participants with right HCP. In the present study, 8 participants with right and 11 participants with left congenital brain damage and 9 neurologically healthy controls were presented with two MI tasks to study this supposed relation between hemispheric processes and behaviour. Participants were instructed to make a laterality judgment on the basis of displayed pictures of hands (either holding a hammer or not) presented in different orientations. For both the control group and the left HCP group, a linear increase in reaction time as a function of angle of rotation was found. Interestingly, no such relationship was observed for the right HCP group, suggesting a disorder in MI for these participants. Collectively, these findings provide new insights into the cause of the anticipatory planning deficits in right HCP individuals.

Keywords: Motor planning; Congenital brain damage; Hemispheric dominance

1. Introduction

Cerebral Palsy (CP) is a condition caused by congenital, non-progressive brain damage. A variety of motor disorders are associated with CP (i.e., spasticity, athetosis, and ataxia), impairing muscle coordination of the affected limb(s). In the case of spastic CP, motor function is characterized by slower movements that consist of more submovements (Chang, Wu, Wu, & Su, 2005; Trombly, 1992, 1993; Utley & Sugden, 1998), a stereotypical shoulder–elbow recruitment order (Steenbergen, van Thiel, Hulstijn, & Meulenbroek, 2000), more variable hand trajectories (van Thiel, Meulenbroek, Smeets, & Hulstijn, 2002), and increased trunk involvement (van Roon, Steenbergen, & Meulenbroek, 2004).

Despite spastic CP being thought of primarily as a motor *execution* disorder, several recent studies involving participants with spastic Hemiparetic CP (HCP; the group under investigation in the present study) showed deficits in anticipatory *planning* as well. More specifically, in tasks that involve complex action sequences, individuals with HCP inadequately anticipate the forthcoming perceptual-motor demands of the task goals (Mutsaarts, Steenbergen, & Bekkering, 2005, 2006; Mutsaarts, Steenbergen, & Meulenbroek, 2004; Steenbergen, Hulstijn, & Dortmans, 2000; Steenbergen, Meulenbroek, & Rosenbaum, 2004). In the majority of these studies, the tasks were performed with the relatively unimpaired hand (see Steenbergen & Meulenbroek, 2006), thereby ruling out possible explanations related to (neuro)motor problems.

Steenbergen et al. (2004), using two object manipulation tasks, examined the differential roles of both hemispheres for motor planning by comparing participants with HCP with left and right brain damage. They showed anticipatory planning problems in participants with right HCP (left brain damage), whereas planning was relatively unaffected in HCP participants with left HCP (right brain damage). More specifically, participants with right HCP did not select an initial grip that allowed them to end the task in a comfortable final posture (i.e., end-state comfort effect; see Rosenbaum, van Heugten, & Caldwell, 1996; Rosenbaum et al., 1990; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993). Also, the combined findings of the studies of Mutsaarts et al. are in line with left cerebral dominance for motor planning, as these studies were exclusively (Mutsaarts

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doi:10.1016/j.neuropsychologia.2006.08.020

et al., 2005), or predominantly (Mutsaarts et al., 2004, 2006) performed with participants with right HCP. Substantial evidence in participants without brain damage (Schluter, Krams, Rushworth, & Passingham, 2001), with left hemispheric stroke (Rushworth, Nixon, Wade, Renowden, & Passingham, 1998; see also Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004; Sabate, Gonzalez, & Rodriguez, 2004), and with apraxia (Goldenberg, 1996; Harrington & Haaland, 1992; Hermsdörfer et al., 1996; Sunderland & Sluman, 2000; Tomasino, Rumiati, & Umilta, 2003; Weiss et al., 2001) further corroborate the left hemispheric dominance for movement planning.

A growing body of evidence suggests that internal movement simulation of part(s) of the body, or motor imagery (MI), involves the same neural mechanisms as those activated when planning and executing overt movements (e.g., Johnson, Corballis, & Gazzaniga, 2001; Wohlschlager, 2001). The specific areas that are found to be activated during MI include the cerebellum, premotor area, supplementary motor area, posterior parietal cortex (Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Lang, Cheyne, Hollinger, Gerschkager, & Lindinger, 1996; Parsons & Fox, 1998; Rao et al., 1993; Wolbert, Weiller, & Büchel, 2003), and possibly even the primary motor cortex (Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Kosslyn et al., 1998; Porro et al., 1996; but see Parsons et al., 1995; Sirigu et al., 1996). As a possible interpretation it has been proposed that MI reflects the conscious experience of an inhibited premotor plan, which would be non-conscious if it were normally executed (Jeannerod, 1994, 1995). However, rather than being dependent on the existence of a completed premotor plan, several studies indicate that MI is critically involved in predicting the consequences of an action, thus contributing to movement planning processes. Firstly, Johnson (2000b) had participants prospectively judge hand-object interactions. In one task, participants were asked to asses how they would grasp objects with a certain orientation, while in another task they were told to actually grasp the objects. The results showed great similarity between the mental and actual performance of the task on both the selection of grips (underhand versus overhand) and the reaction times. Secondly, in a study using a similar task, patients with ideomotor apraxia were shown to be very limited in judging hand–object interactions (Buxbaum, Johnson-Frey, & Bartlett-Williams, 2005). Finally, in a study using transcranial magnetic stimulation (TMS), it was shown that corticospinal excitability – an indirect measure of MI – increased in an object–hand interaction judgment task in comparison with control tasks not involving the prediction of the sensory-motor consequences of an action (Pelgrims, Andres, & Olivier, 2005). Based on these findings, we reasoned that the anticipatory planning deficits that were found previously in individuals with congenital left hemispheric damage may be due to disorders at the level of MI.

The present study was designed to examine this supposed relation between hemispheric processes (participants with left and right hemispheric damage) and behaviour (motor imagery task). Specifically, we presented participants with HCP with tasks that necessitate the mental simulation of movements of their hands. We used two variations on the standard MI task, which involves a hand laterality judgment through mental rotation of pictures of hands (Parsons, 1987, 1994). We were particularly interested in possible cerebral dominance for this task. In a PET study, Kosslyn et al. (1998) demonstrated unilateral left brain activation in motor and premotor areas when participants performed a MI task. Similarly, in a study with stroke patients with unilateral brain-damage, Tomasino, Toraldo, and Rumiati (2003) showed that patients with left brain damage – and not patients with right brain damage – were impaired on a MI task. On the basis of these studies and the studies on left-hemispheric dominance for anticipatory planning in HCP individuals, we hypothesize that MI will be particularly impaired in the participants with right HCP. A neurologically healthy control group was used to establish baseline measures in the different conditions.

For analyzing MI abilities, our main focus is on reaction time (RT) patterns. We assume a lack of linear increase in reaction time as a function of angle of rotation of the stimuli to indicate lack of MI ability. However, we will also analyze the number of incorrect responses. This is done to examine whether the participants with HCP respond above chance level, to rule out random responding. Also, the number of incorrect responses might shed light (albeit more indirectly) on the MI capacity of the participants with HCP. Finally, we will also analyze scores from the Wechsler Intelligence Scale for Children (revised; Wechsler, 1974), to make sure that there is no systematic difference in general intelligence between the participants with left and right HCP. Also, we will examine possible correlations between the IQ scores and the number of incorrect responses.

2. Methods

2.1. Participants

A total of 19 adolescents with spastic hemiparesis as a result of cerebral palsy (11 males and 8 females, mean age = 16.2 years, S.D. = 2.0 years) participated in the study, after signing a written informed consent form. They received 5 € for their participation. The HCP group consisted of 11 participants diagnosed with right spastic hemiparesis (left brain damage; right HCP) and 8 participants diagnosed with left spastic hemiparesis (right brain damage; left HCP). A group of nine neurologically healthy right-handed participants (one male and eight females, mean age = 24.3 years, S.D. = 2.5 years) served as control participants in the study. They were psychology students from the Radboud University in Nijmegen who participated as part of a college research credit requirement. Handedness was established by asking the participants prior to testing what their hand preference was.

This study was approved by the local ethics committee and performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All participants with HCP followed an adapted educational program at the Werkenrode Institute (Groesbeek, The Netherlands), where they were students at the moment of testing. Since they were not patients in a medical clinic, only limited information on individual neuropathology was available. Table 1 lists additional information on the participants with HCP. To examine possible correlations between task performance and general cognitive ability of the participants with HCP, we report the results of the Dutch version of the Wechsler Intelligence Scale for Children-Revised (WISC-R; Wechsler, 1974).

2.2. Experimental stimuli and apparatus

Photographs of identical left and right hands, and photographs of identical left and right hands holding a hammer were used as stimuli (see Fig. 1). All stimuli measured approximately 8 cm in diameter when displayed on a monitor.

Table 1
Participant information (standard deviations in parentheses)

HCP	Participant	Gender	Age	Cause	Total IQ	Performance IQ	Verbal IQ
Left	JA	M	17	Polyomyelitis	48	48	48
	JH	M	17	Cerebral Palsy	82	–	79
	JU	F	17	Cerebral Palsy	–	–	–
	LM	M	17	Cerebral Palsy	98	81	–
	MS	M	16	Cerebral Palsy	68	67	75
	MSCH	M	18	Cerebral Palsy	58	65	57
	PS	M	14	Cerebral Palsy	72	70	81
	SL	F	16	Cerebral Palsy	–	64	90
Mean left			16.5 (1.2)		71 (18)	66 (11)	72 (16)
Right	CJ	F	14	Cerebral Palsy	–	–	–
	DV	F	17	Cerebral Palsy	71	75	72
	GB	M	13	Cerebral Palsy	70	71	74
	HT	F	20	Cerebral Palsy	75	79	77
	JF	M	15	Cerebral Palsy	–	58	101
	MK	M	14	–	58	–	–
	NH	F	14	Cerebral Palsy	98	114	86
	PE	M	15	Cerebral Palsy	–	–	–
	RG	F	19	Cerebral Palsy	61	68	61
	RT	M	15	Cerebral Palsy	–	58	94
	SW	F	19	Cerebral Palsy	63	57	75
Mean right			15.9 (2.4)		71 (13)	73 (19)	80 (13)

The IQ scores are from the Wechsler Intelligence Scale for Children-Revised (WISC-R).

A custom made button box, consisting of a rectangular shaped metal casing (measuring 30 cm in length and 22.5 cm in width) with two adjacent buttons (measuring 17 mm × 17 mm) placed at the centre of the apparatus, was used to record responses with an accuracy of 1 ms. Also, a 17 in. monitor was used to display the stimuli.

2.3. Experimental procedure and design

The participants were seated on a chair positioned in front of a table upon which the button box was placed. All participants responded with the index finger and middle finger of their dominant/unimpaired hand by pressing one of the two buttons on the button box. That is, the participants who responded with the right hand placed the right index finger on the left button and the right middle finger on the right button. Vice versa, the participants who responded with the left hand placed the left index finger on the right button and the left middle finger on the left button. During testing, the participants were instructed to maintain this position. For the participants who responded with the right hand, the button box was placed on the right side of the body's midline, so that the forearm was perpendicular to the body in the saggital plane. In a similar vein, for the participants who responded with the left hand, the button box was placed on the left side of the body's midline. The distance between the eyes of the participants and the monitor, which was placed behind the button box on the table, was approximately 50 cm.

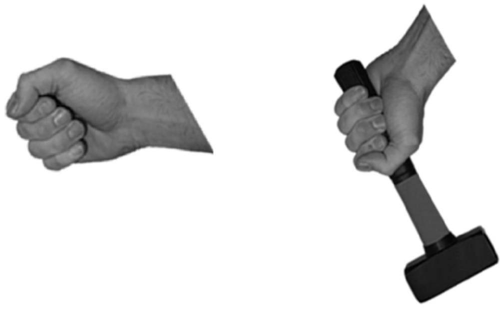

Fig. 1. Two examples of stimuli used. The left stimulus is a right hand in the 0° orientation and the right stimulus is a left hand holding a hammer in the clockwise 150° orientation.

Stimuli were displayed in 12 orientations: upright, upside-down, clockwise 30°, 60°, 90°, 120°, or 150°, and counterclockwise 30°, 60°, 90°, 120°, or 150° (see Fig. 1 for two examples of stimuli in the 0° orientation and clockwise 150° orientation, respectively). All 24 stimuli (12 orientations × 2 different pictures) were presented six times yielding a total of 144 trials. The total number of trials was divided in two blocks for the two different pictures. The presentation order of the blocks was counterbalanced across participants. Trials within each block were randomized. Each block of 72 trials was again divided in six blocks of 12 trials. After every block of 12 trials, presentation of stimuli paused and participants could start the next block of 12 trials by pressing one of the buttons. This procedure was followed so that ample rest periods were present for participants, and the experiment was self-paced to a large degree.

Each trial started with a blank screen for a period of 2 s. Subsequently, a fixation cross appeared in the center of the screen for a random period (between 0.8 and 1.3 s), immediately followed by the presentation of the stimulus. Participants were instructed to press the right button when the stimulus was a picture of a right hand (with or without a hammer). Likewise, the left button had to be pressed when the stimulus was a picture of a left hand (with or without a hammer). No feedback was given regarding the correctness of the responses.

Prior to each block of 72 trials, participants were allowed six practice trials. After each practice trial, visual feedback on the correctness of the responses was presented on the monitor. After the practice trials, each participant confirmed verbally that the task instructions were understood.

2.4. Statistical analysis

We analyzed the mean RTs of the correct responses across the replications using repeated measures analysis of variance (ANOVA). Prior to the use of the ANOVAs we confirmed the normality of the RT distribution by means of Shapiro–Wilk tests for each of the three groups of participants separately. The design consisted of one between-subjects factor (Group) with three levels (right HCP, left HCP, and controls), and one within-subjects factor (Angle of Rotation) with seven levels (0°, 30°, 60°, 90°, 120°, 150°, and 180°). Since we were interested in possible linear relations between RT and angle of rotation, we report the results of the linear polynomial contrasts. Furthermore, we analyzed the data of the incorrect responses by means of a Kruskal–Wallis *H*-test. This was done to examine possible between-subjects effects regarding the amount of errors. Because the number of trials performed for the angles 30°, 60°, 90°, 120°, and 150°, was twice as much as for the angles 0° and 180°, we calculated weighted percentages of incorrect responses across the angles for each individual participant. Also, we used a Wilcoxon Sign–Rank test to statistically analyze possible differences in incorrect responses between left and right hand stimuli for the three different groups. An alpha level of .05 was used for all statistical tests. To examine potential differences between the participants with left HCP and the participants with right HCP with respect to the IQ-scores, we used independent-samples *t*-tests. Finally, we used two-tailed Spearmann rank-order correlations to statistically analyze the correlations between IQ-scores and number of incorrect responses across all HCP participants.

3. Results

3.1. Reaction time

Fig. 2 represents the mean RTs of the correct responses for the three groups (controls, left HCP, right HCP) for the seven individual angles of rotation. The ANOVA showed a significant linear group × angle of rotation interaction effect ($F(2) = 4.139$, $p = .028$, $\eta^2 = .25$), indicating that the linear relation between RT and angle of rotation was different among the three groups. Post hoc analyses showed a linear effect of angle of rotation for both the controls and the left HCP group ($F(1) = 33.896$, $p < .001$, $\eta^2 = .81$, and $F(1) = 12.33$, $p < .01$, $\eta^2 = .64$, respectively). However, for the right HCP group no such effect was found ($F(1) = 3.154$, $p = \text{ns}$, $\eta^2 = .24$). Thus, for participants with right HCP there was no linear increase of RT as a function of increased angle of rotation.

3.2. Incorrect responses

First, we established that the participants in the different groups responded better than chance level. Independent *t*-tests showed that all three groups made significantly less than 50% errors ($t(8) = 12.043$, $p < .001$; $t(7) = 3.28$, $p = .007$; $t(10) = 5.321$, $p < .001$, for the controls, left HCP, and right HCP, respectively).

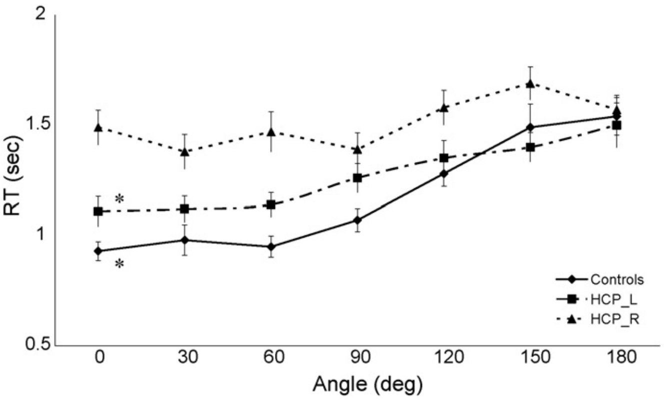

Fig. 2. Mean reaction times of the correct responses at the seven different orientations. Error bars represent standard errors of the means. The solid line with the diamonds represents the controls, the dashed line with the squares represents the participants with left HCP, and the solid/dashed line represents the participants with right HCP. An * indicates that there is a linear relation between RT and angle of rotation.

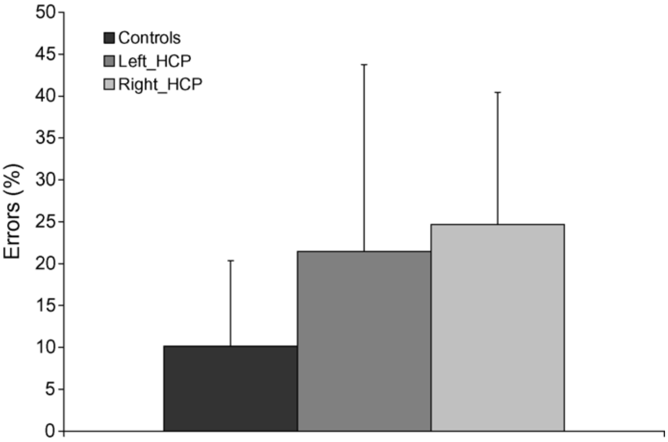

Fig. 3. Incorrect responses (as a percentage of total trials). Error bars represent between-subjects variability (S.D.s). The left bar represent the control participants, the middle bar represent the participants with left HCP, and the right bar represent the participants with right HCP.

Next, we calculated the incorrect responses (as a percentage of total trials) for each group separately (see Fig. 3). Mean ranks for the right HCP group (mean rank = 11.77) and left HCP group (mean rank = 13.00) were much lower than the control group (mean rank = 19.17). A Kruskal–Wallis *H*-test indicated no significant difference between the groups with respect to the percentage of incorrect responses, $\chi^2(2) = 4.374$, $p = \text{ns}$.

Finally, in Fig. 4 the incorrect responses (as a percentage of total trials) for the left and right hand stimuli are represented for the three groups. A Wilcoxon Sign–Ranks test showed that for the left HCP group the mean scores for left hands (mean rank = 4.42) were significantly higher ($z = 2.12$, $p = .034$.) than the mean scores for right hands (mean rank = 1.5). This indicates that they made significantly more errors for the left hand stimuli than for the right hand stimuli. No such hand related differences were found for the controls ($z < 1$) and the right HCP group ($z = 1.067$, $p = \text{ns}$).

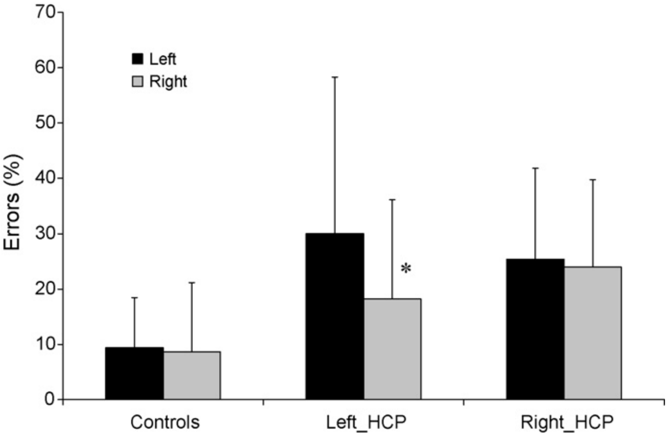

Fig. 4. Incorrect responses (as a percentage of total trials). Error bars represent between-subjects variability (S.D.s). The left bars represent the control participants, the middle bars represent the participants with left HCP, and the right bars represent the participants with right HCP. The * indicates that participants with left HCP made significantly more errors for the left hand stimuli than for the right hand stimuli.

Table 2
Spearmann Rank-order correlations (p-values between parentheses) between number of errors and scores on the Wechsler Intelligence Scale for Children-Revised (WISC-R) for all HCP participants

	Number of errors
Verbal IQ	−.009 (.967)
Performance IQ	−.44 (.101)
Total IQ	−.551 (.052)

3.3. Clinical measures

Independent-samples t-tests ($t < 1$ for total IQ, verbal IQ, and performance IQ) on the Wechsler Intelligence Scale for Children-Revised showed no difference between participants with left and right HCP. In Table 2 the Spearmann rank-order correlations between IQ scores (total IQ, verbal IQ, and performance IQ) and the number of errors are displayed. The analyses showed no significant negative correlations, although the correlation between total IQ and number of errors showed a statistical trend ($p = .052$). The verbal subtest of the WISC-R showed no significant correlation with the number of errors, indicating that there is no relationship between the verbal capacities of the participants with HCP and the performance on the MI tasks in the present study.

4. Discussion

4.1. Main results

Based on the idea that MI plays a critical role in anticipatory planning, which is known to be impaired in individuals with right HCP (Mutsaarts et al., 2004, 2005, 2006; Steenbergen et al., 2004), we hypothesized that internal movement simulation (i.e., MI) is impaired in the participants with right HCP, and not in the participants with left HCP. The results confirmed this hypothesis on the relation between hemispheric processes and behaviour. For both the control group and the left HCP group, linear relations were found between reaction time and angle of rotation. More specifically, larger angles of rotation resulted in longer reaction times, which is in accordance with what is generally observed in such tasks. In contrast, no linear increase in reaction time as a function of the angular distance of the stimuli was observed for the right HCP group. From this we conclude that the participants with right HCP (and not the participants with left HCP) have an impairment at the level of MI. Stated differently, it appears that the ability to internally simulate complex actions is severely reduced in the participants with right HCP.

An alternative explanation for the lack of linear increase of reaction times in participants with right HCP may be that they did not comply with task instruction and/or did not understand the instruction, and their responses are the result of mere guessing. Therefore, in addition to the main RT pattern analyses that were used to examine MI abilities, we also analyzed incorrect responses. This latter analysis showed that the percentage of correct responses of participants with right and left HCP was well above chance level, despite the relatively high percentage of incorrect responses. In addition, the number of incorrect responses of all participants with HCP was not significantly correlated with verbal IQ, suggesting a lack of relationship between the performance on the experimental tasks (i.e., reaction time) and verbal capacities. In light of these findings, we believe that the null-finding on reaction time in participants with right HCP may be attributed to impairments at the level of MI.

If the participants with right HCP did not use MI and neither simply guessed, how did they perform the MI tasks? In a study on internal movement representation, Wilson et al. (2004) established a comparable effect on a MI task in children with developmental coordination disorder (DCD). Specifically, the DCD children showed only a small linear increase in reaction times as a function of angle of rotation, with relatively preserved accuracy. Wilson et al. assumed that the DCD children used viewpoint-independent cues to determine laterality of the hand stimuli, without subsequently mentally rotating the stimuli. Indeed, Parsons (1994) proposed that in the hand laterality judgment task, first an ‘educated guess’ is made, based on such viewpoint-independent cues. Next, the hypothesized hand is mentally rotated to match the orientation of the stimulus, in order to verify the veracity of the initial educated guess. It might be speculated that, in the present study, the participants with right HCP responded without performing this latter part of the task. Such a strategy would account for the relatively high percentage of incorrect responses (see Fig. 3), as well as the lack of linear increase in reaction times as a function of angle of rotation (see Fig. 2), since no verification of the initial ‘educated guess’ takes place.

4.2. Possible processes responsible for anticipatory planning deficits in right HCP

In the following, the implications of present findings are discussed in light of previous studies that showed lack of anticipatory motor planning in complex object manipulation tasks in individuals with right HCP. In both the Mutsaarts et al. (2004, 2006) studies and the Steenbergen, Hulstijn, et al. (2000), Steenbergen, van Thiel, et al. (2000), and Steenbergen et al. (2004) studies, participants with right HCP showed a tendency to grasp objects using an optimal initial grasping pattern. However, in doing so, participants failed to take into account the perceptual-motor consequences of the upcoming task goals. Importantly, this tendency was so strong that the participants with HCP in the Mutsaarts et al. (2006) study could not properly finish the task, due to biomechanically impossible end-postures that were a consequence of the initial grip selected. It has been proposed that anticipatory planning processes necessary to perform such complex object manipulation tasks involve the mental transformation of a somatomotor representation of the effector system, in order to select a proper response (*Imagery as planning theory*; Johnson, 2000a; see also Parsons, 2003). Stated differently, the perceptual-motor consequences of an initial grip on upcoming task demands have to be internally simulated, before the appropriate grasping pattern can be selected. It then follows that a severely reduced capacity to internally simulate movements would seriously complicate the selection of an appropriate grasping pattern. In such case, a strategy might be to select an optimal *initial* grasping pattern, as indeed observed in several studies (Mutsaarts et al., 2004, 2006; Steenbergen, Hulstijn, et al., 2000; Steenbergen, van Thiel, et al., 2000; Steenbergen et al., 2004). Hence, in light of the *imagery as planning theory*, we believe that the present finding of a severely reduced MI capacity may provide new insight into a potential cause of the anticipatory planning deficits of individuals with right HCP.

4.3. Hemiparetic disadvantage

Participants with left HCP showed more incorrect responses for left hand stimuli (corresponding to their affected side) than for right hand stimuli (corresponding to their non-affected side; see Fig. 4). This finding suggests that it is more difficult for the participants with left HCP to mentally simulate movements with their affected hand than with their non-affected hand. We did not find such an effect for the participants with right HCP. That is, these participants did not make more errors for the right hand stimuli (corresponding to their affected side) than for the left hand stimuli (corresponding to their non-affected side). This is not surprising, since we established that – contrary to the participants with left HCP – they appear unable to mentally simulate movements of their hands. Regarding the finding of the participants with left HCP, comparable results were established in a study with seven patients with asymmetrical (right side affected) Parkinson's disease (Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995). They observed that mental simulation of movements in these patients was slower for the affected right hand compared to the non-affected left hand. In contrast, Johnson, Sprehn, and Saykin (2002) found that patients with chronic hemiplegia were more accurate on MI tasks when the affected hand was involved, an effect they termed "hemiplegic advantage". Surprisingly, they did not observe this effect in patients with acute hemiplegia (Johnson, 2000a), healthy subjects (Johnson, 2000b), and patients recovered from hemiplegia. Johnson et al. (2002) speculated that the 'hemiplegic advantage' observed in patients with chronic hemiplegia reflects a constant effort of these patients to imagine movements with the paralyzed limb that they are no longer able to execute. If this speculation is true, this might explain why we did not established a 'hemiparetic advantage' for the participants with left HCP, but rather a 'hemiparetic disadvantage'. In contrast to stroke patients with chronic hemiplegia, individuals with HCP have neuromotor limitations at their affected side from birth onwards. As such, they never experienced 'normal' movement with their affected side. In light thereof, we suggest that the 'hemiparetic disadvantage' observed for the participants with left HCP in the present study, is a result of focusing predominantly on the non-affected side, rather than on the affected side.

4.4. Conclusions

We established a reduced capacity to internally simulate movements in participants with right HCP. We believe this finding might shed new light on the processes responsible for the previously observed anticipatory planning deficits in right HCP individuals. Furthermore, for the participants with left HCP it was more difficult to internally simulate movements with their affected hand, a 'hemiparetic disadvantage'. As a final remark, it must be noted that the groups participating in this study were relatively small, which constitutes a study limitation.

Acknowledgements

We thank those who kindly volunteered to participate in the study. This research was supported by a grant awarded by The Netherlands Organization for Scientific Research (NWO) to the second author for the research project 'Adaptation in movement disorder'.

References

Buxbaum, L. J., Johnson-Frey, S. H., & Bartlett-Williams, M. (2005). Deficient internal models for planning hand-object interactions in apraxia. *Neuropsychologia*, *43*, 917–929.

Chang, J. J., Wu, T. I., Wu, W. L., & Su, F. C. (2005). Kinematical measure for spastic reaching in children with cerebral palsy. *Clinical Biomechanics*, *20*, 381–388.

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

Decety, J., Perani, D., Jeannerod, M., Bettinardi, V., Tadary, B., Woods, R., et al. (1994). Mapping motor representations with PET. *Nature*, *371*, 600–602.

Dominey, P., Decety, J., Broussolle, E., Chazot, G., & Jeannerod, M. (1995). Motor imagery of a lateralized sequential task is asymmetrically slowed in hemi-Parkinson's patients. *Neuropsychologia*, *33*, 727–741.

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

Goldenberg, G. (1996). Defective imitation of hand and finger postures in patients with damage in the left or right hemispheres. *Journal of Neurology Neurosurgery and Psychiatry*, *61*, 176–180.

Haaland, K. Y., Elsinger, C. L., Mayer, A. R., Durgerian, S., & Rao, S. M. (2004). Motor sequence complexity and performing hand produce differential patterns of hemispheric lateralization. *Journal of Cognitive Neuroscience*, *16*, 621–636.

Harrington, D. L., & Haaland, K. Y. (1992). Motor sequencing with left-hemisphere damage—are some cognitive deficits specific to limb apraxia. *Brain*, *115*, 857–874.

Hermsdörfer, J., Mai, N., Spatt, J., Marquardt, C., Veltkamp, R., & Goldenberg, G. (1996). Kinematic analysis of movement imitation in apraxia. *Brain*, *119*, 1575–1586.

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences*, *17*, 187–245.

Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia*, *33*, 1419–1432.

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

Johnson, S. H. (1998). Cerebral organization of motor imagery: Contralateral control of grip selection in mentally represented prehension. *Psychological Science*, *9*, 219–222.

Johnson, S. H. (2000a). Imagining the impossible: Intact motor representations in hemiplegics. *Neuroreport*, *11*, 729–732.

Johnson, S. H. (2000b). Thinking ahead: The case for motor imagery in prospective judgments of prehension. *Cognition*, *74*, 33–70.

Johnson, S. H., Corballis, P. M., & Gazzaniga, M. S. (2001). Within grasp but out of reach: Evidence for a double dissociation between imagined hand and arm movements in the left cerebral hemisphere. *Neuropsychologia*, *39*, 36–50.

Johnson, S. H., Sprehn, G., & Saykin, A. J. (2002). Intact motor representations in chronic upper limb hemiplegics: Evidence for activity-independent action representations. *Journal of Cognitive Neuroscience*, *14*, 841–852.

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.

Lang, W., Cheyne, D., Hollinger, P., Gerschkager, W., & Lindinger, G. (1996). Electric and magnetic fields of the brain accompanying internal simulation of movement. *Cognitive Brain Research*, *3*, 125–129.

Mutsaarts, M., Steenbergen, B., & Meulenbroek, R. G. J. (2004). Assessing the rigidity of the grasping movements of three adolescents with spastic hemiparesis due to a cerebral palsy. *Experimental Brain Research*, *156*, 293–304.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2005). Anticipatory planning of movement sequences in hemiparetic cerebral palsy. *Motor Control*, *9*, 435–454.

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

Parsons, L. M. (1987). Imagined spatial transformation of ones body. *Journal of Experimental Psychology: General*, *116*, 172–191.

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

Parsons, L. M. (2003). Superior parietal cortices and varieties of mental rotation. *Trends in Cognitive Sciences*, *7*, 515–517.

Parsons, L. M., & Fox, P. T. (1998). The neural basis of the implicit movements used in recognizing hand shape. *Cognitive Neuropsychology*, *15*, 583–615.

Parsons, L. M., Fox, P. T., Downs, J. H., Glass, T., Hirsch, T. B., Martin, C. C., et al. (1995). Use of implicit motor imagery for visual shape discrimination as revealed by PET. *Nature*, *375*, 54–58.

Pelgrims, B., Andres, M., & Olivier, E. (2005). Motor imagery while judging object-hand interactions. *Neuroreport*, *16*, 1193–1196.

Porro, C. A., Francescato, M. P., Cettolo, V., Diamond, M. E., Baaraldi, P., Zuiani, C., et al. (1996). Primary motor and sensory cortex activation during motor performance and motor imagery: A functional magnetic resonance imaging study. *Journal of Neuroscience*, *16*, 7688–7698.

Rao, S. M., Binder, J. R., Bandettini, P. A., Hemmeke, T. A., Yetkin, F. Z., Jesmanowixz, A., et al. (1993). Functional magnetic resonance imaging of complex human movements. *Neurology*, *43*, 2311–2318.

Rosenbaum, D. A., van Heugten, C. M., & Caldwell, G. E. (1996). From cognition to biomechanics and back: The end-state comfort effect and the middle-is-faster effect. *Acta Psychologica*, *94*, 59–85.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: Overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and performance XIII*. Hillsdale, New York: Lawrence Erlbaum Associates.

Rosenbaum, D. A., Vaughan, J., Jorgensen, M. J., Barnes, H. J., & Stewart, E. (1993). Plans for object manipulation. In D. E. Meyer, & S. Kornblum (Eds.), *Attention and performance XIV: synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 803–820). Cambridge, MA: MIT Press.

Rushworth, M. F. S., Nixon, P. D., Wade, S., Renowden, S., & Passingham, R. E. (1998). The left hemisphere and the selection of learned actions. *Neuropsychologia*, *36*, 11–24.

Sabate, M., Gonzalez, B., & Rodriguez, M. (2004). Brain lateralization of motor imagery: Motor planning asymmetry as a cause of movement lateralization. *Neuropsychologia*, *42*, 1041–1049.

Schluter, N. D., Krams, M., Rushworth, M. F. S., & Passingham, R. E. (2001). Cerebral dominance for action in the human brain: The selection of actions. *Neuropsychologia*, *39*, 105–113.

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., Hulstijn, W., & Dortmans, S. (2000). Constraints on grip selection in cerebral palsy: Minimizing discomfort. *Experimental Brain Research*, *134*, 385–397.

Steenbergen, B., van Thiel, E., Hulstijn, W., & Meulenbroek, R. G. J. (2000). The coordination of reaching and grasping in spastic hemiparesis. *Human Movement Science*, *19*, 75–105.

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., & Meulenbroek, R. G. J. (2006). Deviations in upper-limb function of the less-affected side in congenital hemiparesis. *Neuropsychologia*, *44*, 2296–2307.

Sunderland, A., & Sluman, S. M. (2000). Ideomotor apraxia, visuomotor control and the explicit representation of posture. *Neuropsychologia*, *38*, 923–934.

Tomasino, B., Rumiati, R. I., & Umilta, C. A. (2003). Selective deficit of motor imagery as tapped by a left-right decision of visually presented hands. *Brain and Cognition*, *53*, 376–380.

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.

Trombly, C. A. (1992). Deficits of reaching in subjects with left hemiparesis: A pilot study. *American Journal of Occupational Therapy*, *46*, 887–897.

Trombly, C. A. (1993). Observations of improvement of reaching in five subjects with hemiparesis. *Journal of Neurology, Neurosurgery and Psychiatry*, *56*, 40–45.

Utley, A., & Sugden, D. A. (1998). Interlimb coupling in children with hemiplegic cerebral palsy during reaching and grasping at speed. *Developmental Medicine and Child Neurology*, *40*, 396–404.

van Roon, D., Steenbergen, B., & Meulenbroek, R. G. J. (2004). Trunk recruitment during spoon use in tetraparetic cerebral palsy. *Experimental Brain Research*, *155*, 186–195.

van Thiel, E., Meulenbroek, R. G. J., Smeets, J. B. J., & Hulstijn, W. (2002). Fast adjustments of ongoing movements in hemiparetic cerebral palsy. *Neuropsychology*, *40*, 16–27.

Wechsler, D. (1974). *Manual for the Wechsler Intelligence Scale for Children-Revised*. San Antonio, TX: Psychological Corporation.

Weiss, P. H., Dohle, C., Binkofski, F., Schnitzler, A., Freund, H. J., & Hefter, H. (2001). Motor impairment in patients with parietal lesions: Disturbances of meaningless arm movement sequences. *Neuropsychologia*, *39*, 397–405.

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 and Child Neurology*, *46*, 754–759.

Wohlschlager, A. (2001). Mental object rotation and the planning of hand movements. *Perception and Psychophysics*, *63*, 709–718.

Wolbert, T., Weiller, C., & Büchel, C. (2003). Contralateral coding of imagined body parts in the superior parietal lobe. *Cerebral Cortex*, *13*, 392–399.