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Anticipatory motor planning in hemiparetic cerebral palsy

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Anticipatory motor planning in hemiparetic cerebral palsy

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Chapter 1

General introduction and outline
Chapter 1

When asked to name the most important skill that humans possess, the skill of grasping objects is rarely mentioned. It is only when circumstances render it more difficult than normal (e.g., in case of a broken thumb) that people realize the fundamental importance and complexity of grasping. It then becomes apparent that almost every daily-life activity involves grasping. At the same time it becomes painfully clear that grasping is only ostensibly a simple skill that actually encompasses a number of complex aspects. These aspects relate to both planning and execution.

For individuals with hemiparetic cerebral palsy circumstances always render it difficult to perform grasping movements. Given the fact that hemiparetic cerebral palsy is a motor function disorder, difficulties in the execution of movements provide the most obvious explanation for the problems these individuals experience with grasping objects. However, the main focus of this thesis is not on aspects directly related to the execution of grasping movements. Rather, different aspects of the planning of grasping movements are examined. In particular, the ability of individuals with hemiparetic cerebral palsy to select an appropriate grasping pattern given a specific task goal is studied.

Selecting an appropriate grasping pattern depends not only on the object’s physical dimensions, but also on what one wants to do with it. Consider the example of a glass that is placed up-side down on a kitchen sink. Picking up this glass in order to place it in the dishwasher would probably involve a grasping pattern with the thumb and index finger at the bottom of the glass and the little finger at the top (see Figure 1a). In this way, a comfortable posture at the end of the movement sequence is allowed. However, if the glass is picked up with the goal of pouring water in it, selecting the same grasping pattern would lead to a very uncomfortable end posture. In this case, a grip with the little finger at the bottom and the thumb and index finger at the top (see Figure 1b) would be more appropriate, for it allows for a comfortable posture after turning the glass up-side down.

This example of daily-life shows that when planning a grasping movement, not only the immediately available perceptual information (e.g., location and orientation of the to-be-grasped glass) needs to be taken into account. Also, information regarding future task goals (e.g., placing the glass in the dishwasher or drinking from it) influences the way a grasping movement is planned. In this thesis, this aspect of planning is referred to as anticipatory motor planning (cf. Johnson-Frey, McCarty, & Keen, 2004). A series of four experimental studies are presented in which the anticipatory motor planning ability of individuals with hemiparetic cerebral palsy is investigated.
To place the studies to be presented in a theoretical framework, I will first give an overview of the most relevant models on the planning and execution of human grasping movements. Subsequently, I will elaborate on the key characteristics defining hemiparetic cerebral palsy. Finally, a preview of the studies is given.

Figure 1a. Grasping pattern with the thumb and index finger at the bottom and the little finger at the top of the glass (placed up-side-down). b. Grasping pattern with the thumb and index finger at the top and the little finger at the bottom of the glass (placed up-side-down).

Planning and executing grasping movements

Most models on the planning and execution of human reaching and grasping assume that the human brain optimizes some parameter(s) to plan a movement trajectory. Examples of such models are the minimum-jerk model (Flash, 1987; Flash, & Hogan, 1985), the minimum torque-change model (Uno, Kawato, & Suzuki, 1989), the minimum-work model (Soechting, Buneo, Herrmann, & Flanders, 1995), the minimum motor-command model (Kawato, 1992, 1996), and the minimum-variance model (Harris, & Wolpert, 1998).
However, the process of selecting a task-appropriate grip is beyond the scope of these models. Numerous studies showed that people are capable of flexibly tuning their grasping movements to task variables such as location, size, and orientation of the to-be-grasped object (e.g., Castiello, Bonfiglioli, & Bennett, 1996; Desmurget, Grea, & Prablanc, 1998; Jeannerod, 1981, 1984; Kudoh, Hattori, Numata, & Maruyama, 1997; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1990; Paulignan, Frak, Toni, & Jeannerod, 1997). Also, as illustrated in the example outlined at the beginning of the introduction, people tend to take into account future task goals when selecting a grasping pattern (e.g., Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992). In the following paragraphs, four models on reaching and grasping are presented that deal with such planning aspects.

**Posture-based motion planning**

In 1990, Rosenbaum, Marchak, Barnes, Vaughan, Slotta, and Engelbrecht reported a phenomenon they termed end-state comfort effect. They observed a tendency of people to sacrifice comfort at the beginning of a movement sequence, to achieve optimal comfort at the end (see also, Elsinger & Rosenbaum, 2003; Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum & Jorgenson, 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993; Short & Caraugh, 1997, 1999). Inspired by this phenomenon, Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, and Engelbrecht developed the knowledge model (1995), capable of predicting pointing behavior.

The main assumption of the knowledge model is that instead of planning a movement trajectory that results in a certain end-posture (e.g., Flash & Hogan, 1985; Uno et al., 1989), a movement is planned by first selecting the most task-appropriate end-posture. The end-postures are selected from the so-called stored posture base, which contains previously adopted postures. Subsequently, the specific movement trajectory is inferred from the start-posture and the selected end-posture.

In 2001, the posture-based motion planning model – a model capable of predicting grasping behavior – was introduced as a successor of the knowledge model (Rosenbaum, Meulenbroek, Jansen, & Vaughan). In addition to the assumptions of the knowledge model, the posture-based motion planning model assumes that one of the most important aspects of motion planning is establishing a so-called constraint hierarchy. That is, a task-defined, prioritized list of requirements. In essence, the constraint hierarchy is a functional definition of a specific task, allowing for multiple constraints to be satisfied simultaneously. Examples of such constraints are avoiding collisions with the to-be-grasped object(s), minimizing
movement-related effort, and optimizing end-state comfort. In this way, future task goals can be taken into account in the selection of a task-appropriate grasping pattern.

**Planning-control model**

Milner and Goodale (1995) suggested that the ventral and dorsal visual streams of the brain serve functionally different purposes. That is, the ventral stream is assumed to be devoted to cognitive representations of objects (perception), whereas the dorsal stream is thought to be involved in the on-line control of action. As an elaboration on this perception-action model, Glover (2004) recently proposed the so-called planning-control model. In this model, the dichotomy between the planning and on-line control of movements is emphasized, a claim substantiated by means of two lines of evidence.

The first line of evidence in support of the idea of separate planning and on-line control phases comes from brain imaging and neuropsychology studies. Several studies show that separate visual representations exist in the brain when people plan a movement versus when the movement is executed (i.e., on-line control). More in particular, movement planning is associated with “activity in a distributed network, including a visual representation in the inferior parietal lobe”, whereas movement control is related to “activity in a separate network including a visual representation in the superior parietal lobe” (Glover, 2004, pp. 2).

The second line of evidence in support of a planning-control dichotomy comes from behavioral studies, indicating that aspects of planning and on-line control influence different phases of a movement. That is, the first phases of a movement primarily reflect the influence of planning aspects, whereas during latter phases the influence of aspects of on-line control become more apparent. The planning system is claimed to be responsible for the initial kinematic parameterization of a movement and – more important in the context of the present thesis – the goal of selecting both a target and a task-appropriate grip pattern. In contrast, the control system is thought to be responsible for on-line adjustments based on the spatial characteristics of the to-be-grasped object. The rationale is that if something changes during the execution of a movement, it most likely involves spatial aspects. For example, the objects’ position or orientation (spatial) might change unexpectedly, whereas the objects’ weight or function (non-spatial) are unlikely to change. In addition to changes that occur during movement execution, the spatial characteristics are also most likely to be erroneously planned.
Internal models

In recent years, the concept of internal models of the motor system has become important in the field of motor control, as the evidence for their existence has grown considerably (see Kawato, 1999). An internal model can be defined as a neural mechanism that is capable of mimicking input/output characteristics, or their inverse, of the motor system. By using sensory-motor mappings, internal models allow the central nervous system to anticipate and adapt to dynamic environments (e.g., Shadmehr, & Mussa-Ivaldi, 1994). Two types of internal models can be distinguished, namely forward models and inverse models.

To predict the outcome of motor commands given a specific state of the motor system, it is assumed the brain uses so-called forward models (Jordan & Rumelhart, 1992). In essence, this type of internal model mimics the normal behavior of the motor system. Important examples of forward models are forward dynamical models and forward sensory models. The former uses information about the dynamics of the motor system (e.g., arm) to predict its future state, whereas the latter uses sensory information to predict the sensory consequences of a planned movement.

An inverse model is conceptually the opposite of a forward model, in that it specifies the motor commands required to achieve a desired outcome (e.g., Blakemore, Wolpert, & Frith, 2002). So instead of generating a prediction of the future state of the motor system as output with a current state and motor commands as input, the output of an inverse model generates a prediction of the necessary motor commands, given a desired future state of the motor system and its current state.

PAM

The PAM (Prospective Action Model; Johnson, 2000; Johnson, Rotte, Grafton, Hinrichs, Gazzaniga, & Heinze, 2002), also called the imagery as planning theory, is designed to provide an explanation for the ability of people to take future task demands in account when planning a grip. Although this model is more descriptive in nature, the conceptual framework it provides regarding the processes underlying anticipatory motor planning is important in the context of the present thesis. The model proposes that anticipatory motor planning of a grip pattern consists of mentally transforming a somatomotor representation of the effector system in order to select a proper response (cf. Parsons, 2003). This means that first somatomotor representations of possible grasping patterns are formed. Next, these representations are mentally transformed (e.g., rotated). As a third step, these transformed somatomotor representations are evaluated in terms of comfort and
biomechanical possibility. Finally, the optimal grasping pattern is selected out of the established somatomotor representations. Importantly, the forming and subsequent mental transformation of somatomotor representations proposed to play a central role in anticipatory motor planning refers to motor imagery, which is a continuous (analog) process.

The four models on human reaching and grasping were presented here neither to critically evaluate them, nor to falsify them on the basis of the findings of the experimental studies of this thesis. Rather, knowledge of the strengths of each of the four models is used to better compare the behavioral findings of the participants with hemiparetic cerebral palsy with ‘normal’ grasping behavior. Hence, in the experimental chapters of this thesis, the different models are used to place the findings within dominant conceptual frameworks to date. In this way, we hoped to gain more insight into the nature of the disorder that was examined.

**Cerebral Palsy**

Since the first report of Cerebral Palsy (CP) by Little in 1861 (the term ‘cerebral paresis’ was used at that time), several definitions have been proposed. In 1959, Mac Keith, MacKenzie, and Polani defined CP as “a persisting but not unchanging disorder of movement and posture, appearing in the early years of life and due to a non-progressive disorder of the brain, the result of interference during its development.”. As suggested by an international working group, Bax (1964) proposed a new definition of CP. The short and most-used version reads: “CP is a disorder of movement and posture due to a defect or lesion of the immature brain.”. Almost thirty years later Mutch, Alberman, Hagberg, Kodama, and Velickovic (1992) attempted to update the definition of Bax. Their modification lead to the following definition: “CP is an umbrella term covering a group of non-progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising in the early stages of development.”. At an international symposium, the definition of CP was recently reconsidered with the goal of acquiring an internationally accepted and adopted definition (Bax, Goldstein, Rosenbaum, Leviton, & Paneth, 2005). As opposed to the previous definitions, it is now emphasized that CP includes only those disorders causing activity limitations, leading to the following definition:
Chapter 1

Cerebral Palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behaviour, and/or by a seizure disorder. (p. 572)

Although the definition of CP changed a number of times over the last 50 years, there are four aspects that are more or less always present. First of all, CP is primarily considered a movement disorder, although the most recent definition acknowledges the high comorbidity of a number of other ‘disturbances’. Secondly, CP is restricted to include only those movement disorders that arise from damage to the brain around birth, thereby ruling out movement disorders arising from brain damage at a later age. Thirdly and related to the previous aspect, CP is considered a developmental disorder, because it influences the way children develop. With a prevalence ranging from 1.5 to 2.5 per 1000 live births in western countries (Paneth, Hong, & Korzeniewski, 2006, for comparable estimates, see also Koman, Smith, & Shilt, 2004; Lin, 2003), it is the most frequently occurring developmental disorder. Fourthly, it is recognized that CP is a non-progressive disorder, which can however change during the lifetime.

Although the different definitions of CP exclude many other existing movement disorders, CP still refers to movement disorder with different symptoms. Hence, CP may still be considered an umbrella term. Therefore, different classification systems have been proposed, based on the nature of the movement disorder and on the limbs affected by the movement disorder.

**Classification by movement disorder**

In one of the most generally accepted classifications, people with CP are divided into three groups, according to the nature of the movement disorder (Sugden & Keogh, 1990). The major group consists of spastic CP (approximately 60%). This type is characterized by “a velocity dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyped excitability of the stretch reflex as one component of the upper motor neuron syndrome” (Lance, 1980, p. 485). It is usually the result of damage to the

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1 Sometimes a fourth group is distinguished, consisting of a mix of the other three groups.
corticospinal tract, which originates in the motor cortex and somatosensory cortex. The majority of participants with CP in the studies presented in this thesis belong to this category. The second type distinguished by Sugden and Keogh is the athetoid type (approximately 30%), characterized by a general slowing of movements. This type of movement disorder results from damage to the thalamus and basal ganglia. The ataxic type (approximately 10%) forms the third group of movement disorders caused by CP, as a result of damage to the cerebellum. This type is characterized by a low muscle tone and poor movement coordination.

**Classification by number of limbs involved**

A second classification system is based on the number of limbs affected. In general, five different types of CP are recognized. The first type is called monoplegia, indicating that only one limb is affected, which is usually an arm. This type does not occur frequently. The second type is called diplegia, which is characterized by all limbs being involved, with the legs being more affected than the arms. The third type is called triplegia, which indicates that both arms and one leg are involved. As for monoplegia, this type is fairly rare. The fourth type is hemiplegia, also called hemiparesis. The participants with CP in the studies presented in this thesis belong to this type. Individuals with hemiplegic or hemiparetic cerebral palsy are characterized by impairments on one side of the body, whereas the other side is relatively unaffected. Quadriplegia is the fifth type, characterized by impairments of both arms and both legs.

**Participants in this thesis**

In the four experimental studies presented in this thesis, the majority of participants of the experimental groups can be classified as having spastic Hemiparetic Cerebral Palsy (i.e., spastic HCP). Because the degree of spasticity is only measured in one study, the abbreviation HCP is used in the rest of the thesis to nominate these participants.

**Outline of the thesis**

Our research into the anticipatory motor planning ability of individuals with HCP is combined in the next four chapters of this thesis. As the chapters were written as stand-alone reports, some overlap (mainly in the introductions) exists.
All four experimental studies were specifically designed to examine different aspects of anticipatory motor planning. To gain more insight into the relationship between planning and execution, in chapters 2 and 4 we also examined movement execution. This was done by analyzing different kinematic measures of the grasping movements performed. Since we were primarily interested in planning processes, rather than processes associated with movement execution, the participants with HCP used their relatively unaffected hand in the studies, with the exception of the study presented in chapter 2. In this way, effects of the neuromotor limitations of the affected hand were not confounding the results. Also, it allowed for more participants, because the ability of individuals with HCP to grasp an object with the affected hand and consequently perform some manipulation with it is severely reduced.

In **Chapter 2**, the question is addressed whether individuals with HCP persist in using a once-chosen grip in successive trials longer before switching to a different grip than neurologically healthy individuals. Furthermore, the effects of different task goals on the selected grip and on the kinematics of the grasping movements were analyzed. Since it was assumed that the adaptation processes regarding the neuromotor limitations are highly individualistic, the data of each of the three participants with HCP were analyzed separately. Subsequently, we compared these data to that of a ‘typical’ control participant, simulated by the average results of 11 neurologically healthy participants. The task consisted of repeatedly grasping a square object of which the position was changed leftwards or rightwards on a trial to trial basis. To examine the effect of task goals on the grip selection, participants were instructed to either lift the object or rotate it back-and-forth after grasping it. The results showed individual differences in adapting to the specific neuromotor limitations with respect to the experimental tasks. That is, the most severely affected participant (GV) maintained a single grip throughout the experiment, irrespective of the position of the object and the task goals. The less severely affected participants (CV and LC) only partially persevered in the previously adopted grips. Although they did not tune their grip selection with respect to the task goals, analyses of their movement kinematics showed that they anticipated the task goals in this respect. Taken collectively, the findings of this explorative study showed that the participants with HCP took their limitations into account when performing movements, but not when planning movements.

The two experiments described in **Chapter 3** were designed to examine in more detail the anticipatory motor planning deviations established in chapter 2. Specifically, in the first experiment the question was pursued whether participants with HCP have the ability to
anticipate the forthcoming perceptual-motor demands of the goal of an action sequence, given that they showed a tendency to ignore future task goals in initial grip selection. The crucial feature of this experiment was that such anticipatory motor planning was necessary to successfully perform the task. A hexagonal knob had to be grasped by choosing one of five possible grasping patterns. The choice of grasping pattern was free. Consequently, the hexagon had to be rotated 60°, 120°, or 180° Clockwise or Counterclockwise. If the hexagon was grasped using a grip that ensured optimal comfort, rotating the hexagon 180° clockwise or counterclockwise was not possible due to the biomechanically impossible the end-position. Participants with HCP showed a large amount of task failures that were persistent throughout the task, whereas no such task failures were observed for the control group. Hence, these findings suggest a deficit in anticipatory motor planning. If individuals with HCP lack the ability to tune their grips to future task goals, the question remains as to what information they do use in selecting a grip. Experiment two was designed to answer the question whether individuals with HCP are sensitive to use context information that is directly available in the task in selecting a grip. To that aim, an arrow was inserted at one of the sides of the hexagon in a position that had no relevance for the action to be planned and executed. For the control participants the location of this arrow did not affect the grips selected, but for the participants with HCP it did significantly influence the grips selected.

To gain more insight in the time aspects of the anticipatory motor planning deficit established in the study presented in chapter 3, anticipatory motor planning for a complex object manipulation task was examined in individuals with HCP. This was done by capitalizing on the complexity and number of elements in movement sequences. This study is presented in chapter 4. The experimental set-up of the previous study was slightly altered to be able to lay bare the different timing aspects. First, a reaction time device was added, to register when participants started a movement sequence. Next, the hexagon was made touch-sensitive, to record the exact moment the participants grasped the hexagon. Finally, the hexagon was made rotation-sensitive. This was done to detect the start of the rotation phase. By measuring these three timing aspects, we were able to examine the effect of planning processes in the course of the execution of a complex object manipulation task. This task consisted of grasping the hexagon following a starting cue, which indicated which of the five possible grips to use. Hence, contrary to the study presented in chapter 3, the choice of grip was not free. In a separate condition, participants were instructed to subsequently rotate the hexagon either 60° or 120° clockwise or counterclockwise. The participants with HCP appeared not to complete their planning processes before movement onset, since the reaction
times were not different for the 60° or 120° rotations. This was contrary to the control participants, who showed longer reaction times for the 120° rotations than the 60° rotations. All in all, the results suggest that the participants with HCP planned the latter parts as the movement unfolds.

It is generally assumed that movements of part of the body (e.g., hands) are simulated in motor imagery (MI) tasks. Under the assumption that MI plays a critical role for anticipatory motor planning, which is disturbed in individuals with HCP as evidenced by the findings of the studies presented in chapters 2, 3, and 4, in Chapter 5 it was hypothesized that MI is affected in individuals with HCP. Specifically, the MI impairments were expected to be more profound in participants with right HCP (left brain damage). This latter prediction was based on results of a study by Steenbergen, Meulenbroek, and Rosenbaum (2004), in which the authors established a hemispheric difference in anticipatory motor planning capacity favoring participants with left HCP (right brain damage). Moreover, the findings of anticipatory motor planning deviations in the studies presented in chapters 2, 3, and 4 corroborated the finding of Steenbergen et al., since most or all participants with HCP in these studies had left brain damage. To be able to establish hemispheric differences, 19 participants with HCP were included for this study. Eight participants had suffered right brain damage and 11 participants left brain damage. These participants and a group of 9 neurologically healthy control participants were presented with two MI tasks. A laterality judgment had to be made on the basis of displayed pictures of hands (either holding a hammer or not) presented in different orientations. The results confirmed our hypothesis, as the participants with right HCP indeed showed MI impairments, in contrast to the participants with left HCP and the controls.

Finally, in Chapter 6 an overview of the main findings of the four experimental studies is provided. Next, new insights that these findings have yielded into the processes underlying the deviant movement behavior of individuals with HCP are discussed. Finally, both clinical implications and future research directions are presented.
Chapter 2

A detailed analysis of the planning and execution of prehension movements by three adolescents with spastic hemiparesis due to cerebral palsy
Abstract

Assuming that primary symptoms of motor disorders can best be distinguished from signs of adaptation through behavioral analyses on an individual basis, the present study provides a detailed analysis of the prehension movements of three adolescents with mild spastic hemiparesis of different etiology. We investigated the extent to which the hemiparetic participants took their movement limitations into account when planning and performing sequences of prehension movements. We examined three indices of flexibility in grip planning in conjunction with an analysis of arm-joint coordination patterns as the movements unfolded. Participants were asked to repeatedly grasp a square object of which the position was gradually changed leftwards or rightwards. In half the trials the goal of the task was to lift the object, in the other half it had to be rotated back-and-forth. Trunk, arm, and hand movements were recorded with two synchronized 3-D motion-tracking systems. The movements of the hemiparetic participants were compared with the average performance of 11 control participants of which the collective data were taken to represent a typical control participant. Whereas one hemiparetic participant (GV) maintained a single grasping pattern throughout the experiment, the other two (CV and LC) only partially persevered in previously adopted grasping patterns. The shoulder contributed more and the wrist contributed less to this perseveration. No effects of task goal were found on grip selection. However, two hemiparetic participants (CV and LC) did tune their hand displacement to the task that followed the grasps. Taken collectively, the results show that the hemiparetic participants took their limitations into account when performing movements, but not when planning movements.

Based on:
Whether the deviant movement patterns that one can observe in atypical populations should be regarded as pathological or the result of long-term adaptation processes has recently been the topic of a lively debate (Carson & Swinnen, 2002; Holt, Fonseca, & LaFliandra, 2000; Latash & Anson, 1996; Levin, Michaelsen, Cirstea, & Roby-Brami, 2002; Roby-Brami, Fuchs, Mohktari, & Bussel, 1997). The present study is aimed at contributing to this debate by examining the planning and execution of grasping movements of three individual adolescents with mild spastic hemiparesis of different etiology. In particular, we investigated the tendency to reuse earlier adopted grasping patterns in a sequential grasping task performed with the affected arm. We expected that symptom severity would be reflected by such a tendency. In addition, we examined the sensitivity of the hemiparetic participants to variations in task goal to explore possible signs of adaptation. To this end, we examined whether the grasping patterns, as well as the hand kinematics and arm joint-coordination patterns during movement execution were tuned to the task that followed the grasping movements, namely rotating or lifting the object.

By analyzing the flexibility in both movement planning and execution we tried to gain more insight into the capacity for adaptation in hemiparesis. Specifically, we hypothesized that if the observed movement patterns would be the result of the impairment proper then the participants would probably be inflexible with respect to changing their grasping pattern as a function of changes in the task set. Alternatively, if the participants would flexibly tune their grasping movements to the imposed changes in the task set, this would indicate a capacity for adaptation to the disorder (for a similar reasoning and experimental proof, see Steenbergen & Meulenbroek, 2003). Before we elaborate on the movement planning and execution levels under study, we will briefly summarize the general characteristics of movements by adolescents with spastic hemiparesis.

**Spastic hemiparesis**

Individuals with spastic hemiparesis have a deviant motor output on one side of the body. Hemiparesis is often accompanied by spasticity, which is characterized by an overall increased muscle tone and a velocity-dependent increase of tonic reflexes. The latter results in excessive activation of skeletal muscles when movements are performed (e.g., Barnes, McLellan, & Sutton, 1994; Lance, 1980). In general, the movements of the affected arm of participants with spastic hemiparesis are slower and show a greater number of submovements than the movements of their unaffected arm (e.g., Steenbergen, Thiel van,
Chapter 2


Group versus individual characteristics

In all of the above mentioned studies, the participants served as their own control group, that is, they were asked to perform the experimental task with the affected and the non-affected arm and subsequent data analyses mainly focused on between-arm differences. However, other studies have shown that, compared to healthy controls, the ipsilesional side of individuals with spastic hemiparesis also shows signs of the disorder (e.g., Hermsdörfer, Ulrich, Marquardt, Goldenberg, & Mai, 1999; Pohl, Winstain, & Onla-or, 1997) which makes the performance of the ipsilesional side a suboptimal basis for comparisons. A different approach was taken here. We reasoned that whereas symptoms generally characterize a group, adaptation processes may be highly individualistic and should therefore better be studied individually. We therefore decided to take the average behavior of a number of control participants as the basis of comparison in our evaluation of the performance of the three hemiparetic participants. Consequently, we took the collective data of 11 control participants to be representative of a typical control participant.

Movement planning

Even though people are generally known to flexibly select a task-appropriate, comfortable grip type in prehension tasks (e.g., Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992) and also to systematically tune their grasping movements to task variables such as the location, size, and orientation of the to-be-grasped object (Castiello, Bonfiglioli, & Bennett, 1996; Desmurget, Grea, & Prablanc, 1998; Jeannerod, 1981, 1984; Kudoh, Hattori, Numata, & Maruyama, 1997; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990; Mamassian, 1997; Paulignan, Frak, Toni, & Jeannerod, 1997), the gradual change of a single task dimension over a series of grasps is known to elicit more or less inflexible solutions. Participants who are asked to repeatedly grasp an object of which the orientation (Rosenbaum et al., 1992) or location (Rosenbaum & Jorgensen, 1992) is changed in small steps from trial to trial tend to persevere in a once chosen grip pattern (for similar findings in drawing, see Meulenbroek, Thomassen, Schillings, & Rosenbaum, 1996).
For example, Rosenbaum and Jorgensen (1992) asked subjects to grasp a horizontal bar placed on a cradle and to position the bar on one of the 14 shelves of a bookcase. Whereas placing the bar on one of the top shelves was most efficiently realized by grasping the bar with an overhand grip, positioning the bar on one of the bottom shelves was most comfortably realized by grasping the bar with an underhand grip. Next to determining the likelihood of the overhand and underhand grip at each of the shelves in random trial sequences, Rosenbaum and Jorgensen examined the extent to which in sequential task performance, a change from the overhand to the underhand grip, and vice versa, depended on the direction in which the bar needed to be placed on the shelves. For this purpose, target shelves were tested in ascending and descending order. The results showed an intermediate range of shelf heights at which participants persisted in reusing the grip they had used on the previous trials. In both the ascending and descending order participants tended to postpone a change of grip. The shelf range in which both grips could occur with equal chance was labeled the range of indifference or the hysteresis region (cf. Kelso, Buchanan, & Murata, 1994).

To investigate whether symptom severity in spastic hemiparesis would be reflected in the planning of sequences of prehension movements we used a paradigm comparable to that used by Rosenbaum and Jorgensen (1992). We asked our participants to repeatedly grasp a square object that, from trial to trial, was gradually shifted rightwards or leftwards. We reasoned that a square object would force a categorical decision regarding how the object would be grasped. In particular, if a subject is asked to grasp a square object with the thumb and fingers touching the opposite sides, and one side of the object is facing the subject, the
hand orientation at the moment the digits make contact with the object falls within one of two categories, that is, defined in an object-centered coordinate system the object can be grasped either with a frontal grip or a lateral grip (see Figure 1).

The hand orientation at grasp completion is the key macroscopic variable in our study. It was anticipated that perseveration in a once adopted task solution, as evidenced by an enlarged hysteresis region, may be a reflection of inflexibility at the level of movement planning (cf. Rosenbaum, Engelbracht, Bushe, & Loukopoulos, 1993; Rosenbaum and Jorgensen, 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993; Short and Cauraugh, 1997, 1999; Steenbergen, Hulstijn, & Dortmans, 2000). We assumed that, as a result of their neuromotor limitations, switching to a different grasping pattern would be more difficult for the hemiparetic participants than for the control participants, as a result of which the hemiparetic participants would persevere in a previously adopted grasping pattern. We therefore expected a larger hysteresis region for these participants. Thus, the effect of the previous grasping pattern on the current one constituted our first index of flexibility at the level of movement planning.

Next to examining the effect of previous task solutions on the grasping pattern, we also examined possible signs of flexibility at the level of anticipatory movement planning. To this aim, we manipulated the goal of the object-manipulation task that followed the grasping movement. In half the trials participants were asked to lift the object and in the other half to rotate it a couple of times along its vertical axis. Studies in healthy controls indicate that when asked to manipulate an object, individuals anticipate which final posture they will adopt at the end of the object-manipulation phase (e.g., Rosenbaum & Jorgensen, 1992; Rosenbaum et al., 1992; Rosenbaum, Vaughan et al., 1993). Subjects sacrifice comfort of the initial grip, in order to ensure a comfortable end posture. Comfortable postures have better signal-to-noise ratios (Rossetti, Meckler, & Prablanc, 1996) as a result of which more precision can be exerted (for experimental proof, see Rosenbaum, Heugten van, & Caldwell, 1996). We anticipated that lifting an object would place higher end-point precision demands on the type of grip that would be selected as compared to rotating the object. Whereas in lifting the object the posture of the hand remains unaltered (except for a vertical translation), hand posture is constantly changing during rotation. We therefore hypothesized that the need for planning a comfortable end posture would be larger in the lifting task than in the rotating task.

In a recent study, Steenbergen, Hulstijn et al. (2000) suggested that hemiparetic adolescents do not take into account the end posture of the hand when they plan a grasping action. Indeed, if the hemiparetic participants only plan the start of their actions, the hand
orientation at the moment of grasping the object would not vary as a function of the goal of the subsequent object-manipulation task. Thus, the effects of task goal on the selected grip constituted our second index of flexibility at the level of anticipatory movement planning.

**Movement execution**

We also studied anticipation at the level of movement execution. One of the first studies in which the effects of the task goal on the kinematics of reach-to-grasp movements were examined was performed by Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas (1987). They contrasted the three-dimensional movement trajectories of grasping a disk that was either thrown in a large box or placed into a tightly fitting well. The kinematics of the reaching movements were found to vary considerably, particularly with respect to the moment of peak velocity. It appeared that the deceleration phase increased in duration when the precision demands were higher. In another study, Marteniuk et al. (1990) demonstrated that the moment of peak grip aperture also occurred earlier when the precision demands of a prehension task were higher, that is, when smaller objects were to be grasped. Based on these findings, we expected earlier occurrences of peak aperture and peak velocity if participants anticipated the higher precision requirements for lifting the object compared to rotating it. Thus, at the level of anticipatory movement execution, the effect of task goal on the reach kinematics served as our third index of flexibility. A lack of scaling of the occurrence of peak velocity and peak aperture to variations in task context was taken to be an indication of inflexibility at the level of movement execution.

Upon determining anticipation at the level of movement execution, our final assessment concerned the functional reorganization of the movement system during the execution of the grasping movements, via an examination of the relative contribution of the shoulder, elbow, and wrist segments to the between-trial switches in hand orientation. Contemporary research has shown an increased involvement of proximal segments (e.g., shoulder and trunk) as compared to distal segments (e.g., elbow and wrist) during the execution of pointing movements (Archambault, Pigeon, Feldman, & Levin, 1999; Levin, 1996; Levin et al., 2002; Thiel van et al., 2002) and prehension movements (Roby-Brami et al., 1997; Steenbergen, Thiel van et al., 2000) in participants with spastic hemiparesis. Next to examining the absolute contribution of the movement segments, studies on reaching in hemiparetic participants also focused on inter-segmental coordination, hence, within-trial movement unfolding in the temporal domain (Levin; Archambault et al.; Steenbergen, Thiel van, et al.). As an example, Steenbergen, Thiel van et al. showed that movement coordination
at the affected side was segmented. Initially, there was a large trunk and shoulder joint involvement, followed by an increased involvement of the elbow joint. Based on these findings we assumed a larger contribution of the proximal segments to the between-trial switches in hand orientation. Thus, contrary to other studies, in which the segmental coordination was treated as a within-trial phenomenon, we treated this functional reorganization as a between-trial phenomenon.

In short, for the hemiparetic participants, we expected enlarged hysteresis regions, but no effects of the task goals on the selected grip and the reach kinematics. Finally, we expected to find a between-trial proximo-distal effect in the functional reorganization to the (possible) hysteresis effects.

**Method**

**Participants**

Three hemiparetic adolescents, CV, LC, and GV (mean age 16 years, SD 2 years) and 11 healthy control participants (mean age 22.5 years, SD 3.6 years) participated on a voluntary basis. At the moment of testing, the hemiparetic participants were students of the Werkenrode Institute (Groesbeek, Netherlands).

![Experimental set-up diagram]

**Figure 2.** The experimental set-up. The two Optotrak systems are depicted at the top left and right-hand side of the figure, with the dashed lines depicting the angle at which the IREDs are visible to the camera units. Tabletop showing the object positions numbered 1 to 7 and the object (both in top view and in side view). The positions of the IREDs are indicated by filled circles on top of the rectangular object and on the index finger, thumb, hand, wrist, elbow, and both shoulders of the participant sitting in front of the table. The position of the reference coordinate system (xyz) is indicated.
The Netherlands), where they followed an adapted educational program. The control participants were psychology students of the University of Nijmegen. The hemiparetic participants were selected on the basis of (1) being diagnosed as having hemiparesis and (2) the ability to reach and grasp with the affected hand to perform the experimental task under study. Of two participants the right side was most affected and in the other participant the left side was most affected. As the hemiparetic participants were students of a school for special education, information in the medical records about the individual neuropathology was limited (see Table 1). However, in order to characterize the participants in terms of the severity of the disorder, we performed several clinical tests (see Table 2 for data).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (years)</th>
<th>Diagnosis</th>
<th>Sex</th>
<th>Etiology</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>15.5</td>
<td>Right spastic hemiparesis</td>
<td>M</td>
<td>CP during birth</td>
<td>CARA, Psychomotor Retardation</td>
</tr>
<tr>
<td>LC</td>
<td>14.3</td>
<td>Left spastic hemiparesis</td>
<td>M</td>
<td>CC at age 10 years</td>
<td>-</td>
</tr>
<tr>
<td>GV</td>
<td>18.3</td>
<td>Right spastic hemiparesis</td>
<td>F</td>
<td>HE at age 2 years</td>
<td>Epileptic</td>
</tr>
<tr>
<td>Controls</td>
<td>22.5</td>
<td>Right handed</td>
<td>4 M/7 F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note. CP: Cerebral Palsy. CC: Contusio Cerebri. HE: Herpes Encephalitus. CARA: Chronic Aspecific Respiratory Affection.*

To examine the level of hand function impairment, two dexterity tests, the Purdue Pegboard test (Tiffin, 1968) and the Box and Block test (Mathiowetz, 1985), were administered according to the instructions in the test-protocols. The estimated reliability of the Purdue Pegboard test for the three-trial scores (administered in this study) ranges from .82 to .91 (Tiffin). The test-retest reliability at six-month intervals of the Box and Block test has been reported as rho coefficients of .937 and .976 for the left and right hand, respectively (Mathiowetz 1985). While the former is a test of fine manipulative skills, the latter is a test of gross dexterity of the kind that is needed for the present task. Furthermore, the Ashworth Scale of Spasticity (Ashworth, 1964) was administered by a trained physical therapist to establish the level of the spasticity at the elbow and wrist flexors and extensors. The intrarater reliability of the Ashworth scale was indicated excellent or good (weighted kappa ≥ .75 and .4, respectively) in 38 out of 40 evaluations. Furthermore, the interrater reliability was good (Kendall W = .598-.792), with statistically significant agreement (all P< .001) found among
raters (Brashear et al., 2002). On the basis of these assessments the hemiparetic participants were ranked from least affected to most affected (CV, LC, and GV, respectively). Finally, the active and passive ranges of motion of the elbow and wrist joints were established (Clinical Goniometer, MIE medical research Ltd.; see Boone, Azen, Lin, Spence, Baron, & Lee, 1978; Horger, 1991). With the passive scores we established the limits of range of motion that were biomechanically possible,

Table 2
Clinical Evaluation of the Three Hemiparetic Participants.

<table>
<thead>
<tr>
<th></th>
<th>CV</th>
<th>LC</th>
<th>GV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dexterity (test scores)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purdue Pegboard</td>
<td>11.7 (13.3)</td>
<td>4.7 (15.7)</td>
<td>2 (13.3)</td>
</tr>
<tr>
<td>Box and Block test</td>
<td>42 (54)</td>
<td>34 (66)</td>
<td>23 (34)</td>
</tr>
<tr>
<td><strong>Spasticity (Ashworth Scale)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist palmar flexion</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (0)</td>
</tr>
<tr>
<td>Wrist palmar extension</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1 (0)</td>
</tr>
<tr>
<td>Elbow flexion</td>
<td>0 (0)</td>
<td>1 (0)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Elbow extension</td>
<td>1 (0)</td>
<td>1 (0)</td>
<td>1 (0)</td>
</tr>
<tr>
<td><strong>Range of motion (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist palmar flexion (passive)</td>
<td>100 (80)</td>
<td>70 (80)</td>
<td>115 (95)</td>
</tr>
<tr>
<td>Wrist palmar flexion (active)</td>
<td>80 (70)</td>
<td>50 (65)</td>
<td>90 (70)</td>
</tr>
<tr>
<td>Wrist dorsal flexion (passive)</td>
<td>80 (80)</td>
<td>80 (80)</td>
<td>80 (85)</td>
</tr>
<tr>
<td>Wrist dorsal flexion (active)</td>
<td>75 (70)</td>
<td>65 (70)</td>
<td>65 (65)</td>
</tr>
<tr>
<td>Elbow flexion (passive)</td>
<td>150 (155)</td>
<td>155 (150)</td>
<td>160 (155)</td>
</tr>
<tr>
<td>Elbow flexion (active)</td>
<td>140 (150)</td>
<td>140 (135)</td>
<td>150 (150)</td>
</tr>
<tr>
<td>Elbow extension (passive)</td>
<td>185 (185)</td>
<td>170 (180)</td>
<td>185 (185)</td>
</tr>
<tr>
<td>Elbow extension (active)</td>
<td>180 (185)</td>
<td>175 (180)</td>
<td>155 (180)</td>
</tr>
<tr>
<td><strong>Difference in passive and active range of motion (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrist palmar flexion</td>
<td>20 (10)</td>
<td>20 (15)</td>
<td>25 (25)</td>
</tr>
<tr>
<td>Wrist dorsal flexion</td>
<td>5 (10)</td>
<td>15 (10)</td>
<td>15 (20)</td>
</tr>
<tr>
<td>Elbow flexion</td>
<td>10 (5)</td>
<td>15 (15)</td>
<td>10 (5)</td>
</tr>
<tr>
<td>Elbow extension</td>
<td>5 (0)</td>
<td>5 (0)</td>
<td>30 (5)</td>
</tr>
</tbody>
</table>

Note. Displayed are the values for the affected side and the less affected side (in parentheses). Dexterity was assessed via scores on the Purdue Pegboard test (average score of three test runs of the one-hand subtest) and Box-and-Block test (number of blocks transported in 60 seconds). Spasticity was evaluated via the Ashworth Scale of spasticity administered by an experienced physical therapist (0=no resistance, to 4=rigid joint). Passive and active ranges of motion (in degrees) of the wrist and elbow joint are displayed. Theoretically, maximum elbow extension reaches 180 degrees. However, due to hypermobility of the elbow joint in two participants (CV and GV) values of 185 degrees were found, indicative of over-extension of the elbow. Finally, the difference between passive and active range of motion measures are displayed as an indication of the portion of the biomechanically available range of motion that could not actively be used by the participant. Participants are ranked from less severe (CV) to more severe (G) based on the different measures.
whereas the active scores showed the range of motion that could actually be covered by the participant. The difference between both scores informed us about the size of the biomechanically possible range of motion that could not be used functionally by the participant, potentially due to muscle weakness. The results of this assessment are also presented in Table 2.

All participants signed an informed consent. This study has been approved by the local ethics committee and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

**Experimental set-up and apparatus**

The participants were comfortably seated in an ergonomic chair positioned in front of a table, at waist level, such that the forearm paralleled the floor if placed on the table. In the tabletop, measuring 136 cm in length and 80 cm in width, seven horizontally equidistantly spaced holes, with a diameter of 4 cm were drilled (see Figure 2). The distance between the holes as measured from the edges was 10 cm. The distance between the front edge of the table (i.e., the positive x-axis) and the holes as measured from the edges was 21 cm. A 21-inch monitor was placed behind the table facing the participants. A rectangular object (see Figure 2) was used in the experiment. The circular bottom of this object measured 12 cm in length and had a diameter of 4 cm and could be fitted in one of the holes. The upper part of the object measured 10 cm in length and the sides forming a square measured 6 cm. This upper part was visible for the participants when placed in a hole. Two synchronized 3-D motion-tracking systems (Optotrac 3020), placed at both sides of the table at a height of approximately 230 cm, were used to record the position of seven Infra Red Emitting Diodes (IREDs) attached to the index finger, thumb, hand, wrist, elbow, and both shoulders (see Figure 2). The angle between the cameras was approximately 120 degrees. Furthermore, the position of a rigid body placed on top of the object was recorded (Bouwhuisen et al. 2002). The rigid body consisted of three IREDS, and was used to provide real-time feedback to the participant about task progress. Sampling rate was set at 100 Hz and dynamic spatial error did not exceed 0.3 mm. Information on possible loss of data due to IRED obscurity was obtained after each trial. In case of missing data, that particular sequence of 7 trials was repeated after finishing the sequence. This was done in approximately 1 % of the recordings. In addition, a digital camera taped the performance of the participant during the experiment without recording the head (for privacy reasons).
Design and procedure

At the start of each trial the participants placed their hand on the tabletop, in front of position 4 (see Figure 2). Following a GO signal—a computer generated beep—the participants grasped the object that was placed in one of the holes. The instruction was to grasp the object such that the thumb and the four fingers contacted the object on opposite sides. All seven positions of the object were within reaching distance. Once the object was grasped, the participants had to either lift it for approximately five cm or rotate it back-and-forth around its vertical axis approximately six times. The participants were instructed whether they had to lift or rotate the object prior to the start of a new trial. The hemiparetic participants performed the task with their affected hand and the control participants with their dominant hand. Participants received on-line visual feedback displayed on a computer monitor in the form of a digitized picture that moved in vertical direction upon lifting or rotating the object. When the picture touched a horizontal line at the top of the screen, an acoustic signal was generated and the picture fell down to the bottom of the screen. The acoustic signal together with the fallen picture was the cue for the participants to let go of the object and return to the start position. The total experiment consisted of four conditions, defined by task goal (rotate or lift) and direction (rightwards or leftwards, consisting of one trial for each of the seven holes). Each condition was replicated five times. This yielded a total of 140 trials: 2 task goals * 2 directions * 7 object positions * 5 replications. Conditions were blocked with respect to task goal. Within a task goal block, five replications of the rightward direction and five replications of the leftward direction were tested in a random order. Although the controls were generally faster, the experiment took approximately half an hour to complete for the controls as well as the hemiparetic participants. The reason for this was that originally the controls were tested on two additional object positions.

Prior to the start of the actual experiment, participants were allowed to practice the two tasks, to become accustomed to the task and to find a comfortable sitting posture that they were asked to maintain during the experiment. On average, practice sessions took 10 minutes, including instructions.

Data analysis

The task participants had to perform consisted of grasping the object and subsequently performing one of the two manipulations, that is, either rotating or lifting it. The data analyses were focused on the reach phase, that is, the phase demarcated by the start of the movement
(determined by the moment at which the tangential wrist velocity was more than 3 percent of peak velocity; see t1 in Figure 3) and object contact (determined by the moment at which the wrist velocity was less then 3 percent of peak velocity; see t4 in Figure 3). Within this reach phase we determined the percentage of time to peak velocity (t2, Figure 3) and the percentage of time to peak aperture (t3, Figure 3).

Hand orientation was computed as the angle between the front edge (i.e., the positive x-axis, see Figure 2) of the table and the horizontal projection of the vector connecting the IRED on the index finger to that on the thumb. Two categorically distinct grip patterns were possible (see Figure 1). Via analysis of the video record we established that a between-trial hand orientation change of 30 degrees at the moment of object contact (t4) corresponded to a categorical switch in grip pattern. For each sequence of seven object positions we determined the position at which a switch into another grip pattern was made, namely, we determined the switch point in the sequence (see Figure 4 for 2 examples). The average switch point across replications for the direction

leftwards was subtracted from the average switch point for the direction rightwards to determine the size of the hysteresis region. In this way, the hysteresis region was expressed as a single value\(^2\) indicating the average number of positions that a switch was postponed as a function of sequence direction.

Hemiparetic participant LC was the only participant that used his left hand. Since the experimental setup was symmetrical, the switch points of participant LC were mirror-images of the switch points of the other participants (e.g., 0\(\rightarrow\) 8; 1\(\rightarrow\) 7 etc.). Likewise, we transformed his switch point data for data analysis purposes.

Finally, three joint angles were computed at the moment of grasping (t4): wrist angle, elbow angle, and shoulder angle. To prevent the problem of not being able to discriminate between flexion and extension of the wrist (for example, an 80-degree angle could equally imply extension and flexion), we defined the wrist angle as the (2-D) angle enclosed by the horizontal projection of the vector between the hand IRED and wrist IRED, and the vector between the wrist IRED and elbow IRED. The elbow angle was computed by taking the 3-D vector between the wrist IRED and elbow IRED, and that between the elbow IRED and shoulder IRED, and consequently computing the angle between them. For the shoulder angle

\(^2\)Although the individual switch points are by definition whole numbers, the average switch points across replications can result in a fraction of this whole number. Consequently, the size of the hysteresis region is displayed as a fraction.
the same procedure was followed, but here the vector between the elbow IRED and shoulder IRED, and that between the shoulder IRED and the IRED on the contralateral shoulder, were used.

\[ a \]

\[ b \]

*Figure 3a*. Raw data of a representative trial in the rotation condition of hemiparetic participant CV. The tangential wrist velocity profile (mm/s) is displayed in the top graph. The graph at the bottom represents the grip aperture profile. Four critical landmarks are indicated with arrows, index 1-4 (see section on data analyses). *b*. The two graphs display raw data of a typical rotation trial of a control participant.

**Statistical analysis**

When assessing the effects of the task variables in the control group, the switch-point data and the reach kinematics were analyzed by using paired-samples t-tests. We used
independent-samples t-tests when analyzing the performance of the individual hemiparetic participants.

In addition, we evaluated the statistical significance of the relationship between each of the three joint angles (wrist angle, elbow angle, shoulder angle) and the hand orientation angle by means of permutation tests (Edgington, 1995; Good, 2000). We were interested in the relationship between the effect of sequence direction on hand orientation and on each of the three joint angles. Specifically, with this analysis we examined these three relations to capture the relative contribution of each of the three joints to the between-trial switches that were found for hand orientation.

To this aim, we first determined a difference-angle in each of the seven object positions, for hand orientation, shoulder angle, elbow angle, and wrist angle, respectively. A difference-angle at a certain object position was defined as the average angle in the rightward condition minus the average angle in the leftward condition. Second, we determined a vector of difference-angles of length seven, corresponding to the seven object positions. Again, this was done for hand orientation, shoulder angle, elbow angle, and wrist angle. The relation between two vectors of difference-angles – the hand orientation vector and each of the three joint angle vectors - was expressed as the cosine value between these vectors. If the two
vectors of difference-angles are nearly proportional, indicating similar effects of sequence
direction for both vectors, this would result in a cosine value close to one.

To test statistical significance of the cosine values we performed a permutation test
(Edgington, 1995; Good, 2000). Specifically, we tested the null hypothesis of statistical
independence between two vectors of difference-angles. First, we performed a random
permutation of the seven elements of the vectors of difference-angles for each of the joint
angles. The elements of the hand orientation vector remain unchanged. Second, the cosine
value of each of these permuted difference-angle vectors and the hand orientation
difference-angle vector was calculated. This resulted in a total of 5039 (number of
permutations of a vector with length 7, i.e. 7!-1) cosine values for each joint-hand orientation
combination. Finally, the proportion of random permutations for which the cosine value was
larger than the observed value constituted the approximation of the p-value. For, example if
the observed cosine between shoulder and hand orientation is .9 (indicating a tight
relationship between them), and only 50 cosine values of the permuted of difference-angles
vector of the shoulder and the vector of hand orientation were higher then .9, the resulting p-
value was .01 (50/5039).

Results

Clinical evaluation

The three hemiparetic participants were ranked on the basis of their scores on the
Purdue Pegboard and Box and Block test, and the level of spasticity of the affected side as
assessed by the Ashworth Scale of Spasticity. As is clear from Table 2, ranking based on
these three assessments produced similar results. That is, dexterity decreased and spasticity
increased from participant CV, via LC to GV. Moreover, especially participant GV differed
from the other two participants in level of spasticity. Increased levels of spasticity were found
for this participant in both the wrist and elbow joint. Resistance to passive stretch was
especially large for palmar flexion of the wrist (Ashworth 2: Increased resistance for the
major part of the range of motion). Largely in line with this ranking were the active and
passive range of motion measurements of the wrist and elbow joints. If the difference scores
in passive and active range of motion are regarded, nearly similar values for participant CV
and LC were found, with slightly smaller difference scores for participant CV. Again,
participant GV deviated most. For elbow extension the difference between active and passive
range of motion was large (amounting to 30 degrees) as was also the case for wrist flexion (amounting to 25 degrees). Put differently, this participant was unable to utilize the biomechanically possible range of motion of the elbow and wrist joints. As the passive ranges of motion of the wrist and elbow joint were equal or even larger in participant GV compared to participants CV and LC, the reduced active range of motion in this participant can not be ascribed to biomechanical limitations, but is potentially due to muscle weakness. Summing up, all clinical assessments resulted in the same ranking of the participants from less to more severe of CV, LC, to GV.

First the results related to planning are presented: (1) the position of the hand orientation switches and the size of the hysteresis region collapsed across both task goals, (2) the effects of the two task goals (i.e., lifting vs. rotating the object), on the position of the hand orientation switches and the size of the hysteresis region. Next, the results related to execution are presented: (3) the effects of the two task goals on the reach kinematics, and (4) the contribution of the three joint angles to the between-trial switches in hand orientation.

Planning: Hand orientation switches and size of the hysteresis region (collapsed across both task goals)

In Table 3, the switch-point data and hysteresis regions together with the statistical values are presented. It was found that the ‘typical’ control participant, as well as hemiparetic participants CV and LC, postponed a switch between grip patterns as a function of the sequence direction. As expected, the size of the hysteresis regions of both hemiparetic participants CV and LC was larger than that of the ‘typical’ control participant, namely by 1.15 positions (1.4 positions versus 0.25 position).

Unexpectedly, hemiparetic participant GV did not switch at all between the two possible grasping patterns. She used the same grasping pattern throughout the range of object positions, irrespective of sequence direction (lateral grip, see Figure 1). Consequently, despite the fact that this participant persevered in the initially selected grip there was no hysteresis region observed for this participant.
Planning: Hand orientation switches and size of the hysteresis region. Effects of task goal

The average locations of the switch points and the size of the hysteresis region were also analyzed as a function of the two task goals (see Table 3). For the ‘typical’ control participant, a significant difference was found in the size of the hysteresis region between the lift condition and the rotation condition. Whereas the rotation condition yielded a significant hysteresis region, in the lifting condition the hysteresis region was not significant. For the three hemiparetic participants no differential effect of task goal was found on the size of the hysteresis region. For participants CV and LC, both task goals yielded significant hysteresis regions. Due to the absence of switches in grasp pattern throughout the experiment for participant GV (only the lateral grip pattern was used by this participant, see Figure 1), all hysteresis regions were zero and did not vary as a function of task goal.

Execution: Reach kinematics. Effects of task goal

In Table 4, the means and the standard deviations of the percentage of time to peak velocity and percentage of time to peak aperture are presented for both task goals separately. For the ‘typical’ control participant, peak velocity

Table 3

Switch Points in Hand Orientation and Hysteresis Regions (H. Region) for the ‘Typical’ Control Participant (TCP) and the Three Hemiparetic Participants

<table>
<thead>
<tr>
<th>Condition</th>
<th>Direction</th>
<th>TCP</th>
<th></th>
<th>CV</th>
<th></th>
<th>LC</th>
<th></th>
<th>GV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Overall</td>
<td>Rightwards</td>
<td>5.49</td>
<td>0.58</td>
<td>6.1</td>
<td>0.74</td>
<td>7.1</td>
<td>0.88</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Leftwards</td>
<td>5.24</td>
<td>0.60</td>
<td>4.7</td>
<td>0.48</td>
<td>5.7</td>
<td>1.25</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td></td>
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<td>1.4*</td>
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</table>

*Note. The SD’s for the TCP are mean within-subjects Standard Deviation. \( p < .05 \). **\( p < .005 \).
was attained earlier in the lift condition compared to the rotation condition, \( t(10) = 5.66, p < .001 \). By the same token, hemiparetic participants CV and LC reached peak velocity earlier in the lift condition compared to the rotation condition, \( t(131) = 3.92, p < .001 \), and \( t(132) = 7.54, p < .001 \), respectively. For hemiparetic participant GV, no such difference among lifting and rotating was found for the relative occurrence of peak velocity, \( t(133) = 1.43, p = ns \).

For the percentage of time to reach peak aperture similar results were found. The percentage of time to peak grip aperture occurred earlier in the lift condition than in the rotation condition in the ‘typical’ control participant \( t(10) = 4.58, p = .001 \) and both hemiparetic participants CV and LC, \( t(131) = 6, p < .001 \), and \( t(132) = 8.58, p < .001 \), respectively. In contrast, for hemiparetic participant GV, the percentage of time to grip aperture occurred later in the lift condition than in the rotation condition, \( t(133) = 3.97, p < .001 \).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Task goal</th>
<th>TCP</th>
<th>CV</th>
<th>LC</th>
<th>GV</th>
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<tr>
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</table>

*Note.* The SDs for the TCP are mean within-subjects Standard Deviation. *\( p < .005 \). **\( p < .001 \).

The contribution of the three joint angles to between-trial switches in hand orientation.

In Figure 5 the difference-angles (deg) for hand orientation (circles), wrist angle (triangles), elbow angle (squares), and shoulder angle (diamonds) are displayed. For the ‘typical’ control participant and hemiparetic participants CV and LC large hand orientation difference-angles can be observed at object locations 4 – 7 (particularly at location 5, as at this location the grip type selected depended most on the sequence direction), corresponding to the object locations were switches in hand orientation were made (see Table 3). As can be observed in Figure 5, and confirmed by the cosine values and permutation tests (see Table 5),
for the ‘typical’ control participant the wrist joint contributed most to switches in hand orientation, followed by the shoulder angle. The elbow did not contribute significantly to switches in hand orientation. A near similar pattern was found for hemiparetic participants CV and LC. For both participants the contribution of the wrist joint was again largest. However, for both participants the relative contribution of the shoulder joint was larger compared to the ‘typical’ control participant (see Figure 5, and cosine values in Table 5). In addition, shoulder contribution increased from participant CV to LC. Finally, although hemiparetic participant GV did not switch her grasp pattern throughout the experiment (as evidenced by the near flat lines for hand orientation in Figure 5) we performed the same tests. As expected, the tests resulted in non-significant p-values (see Table 5).

![Graphs showing difference angles for hand orientation, wrist angle, elbow angle, and shoulder angle for TCP, CV, LC, and GV](image)

**Figure 5.** The four graphs represent the ‘Typical’ Control Participant (TCP) and hemiparetic participants CV, LC, and GV, respectively. In these graphs the difference-angles for the two directions (rightwards and leftwards) are displayed for the seven positions of the object for hand orientation (circles), wrist angle (triangles), elbow angle (squares), and shoulder angle (diamonds).
Table 5
Cosine Values for the 'Typical' Control Participant (TCP) and the Three Hemiparetic Participants

<table>
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<tr>
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<th>TCP P</th>
<th>CV Cosine</th>
<th>CV P</th>
<th>LC Cosine</th>
<th>LC P</th>
<th>GV Cosine</th>
<th>GV P</th>
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<td>.04</td>
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Note. Ho = hand orientation, P represents the p-value of the permutation test.

Discussion

In the present study we investigated the extent to which three hemiparetic participants who differed in terms of symptom severity took their movement limitations into account when planning and when performing sequences of prehension movements.

Movement planning

The data on the between-trial switches in hand orientation showed the presence of a hysteresis region for the ‘typical’ control participant, which was expected on the basis of previous work by Rosenbaum and Jorgensen (1992) and Kelso et al. (1994). Hemiparetic participants CV and LC also showed hysteresis effects, but the size of their hysteresis regions was larger compared to the ‘typical’ control participant. These findings indicate that the current grip type that these participants employ is to a large degree dependent on the grip type that was used on the previous occasion. Stated differently, they are less flexible in changing their grip type compared to the ‘typical’ control participant. Remarkably, the third hemiparetic participant (GV) who was most severely affected showed no switches in hand orientation at all, but employed the same grip type during the entire experiment. At first sight this deviant task solution appears extremely inflexible, as attaining the same grip type in all object locations leads to awkward postures in some of these positions. Why did this participant chose this ostensible inflexible task solution? To find an answer to this question,
we have to revert to the clinical evaluation (Table 2).Participant GV deviated from the other two hemiparetic participants with respect to the level of spasticity and differences in active and passive range of motion. Contrary to the other two hemiparetic participants, she had an increased level of spasticity in both elbow and wrist joints. In addition, the active range of motion for the elbow extension was decreased to a large degree, amounting to a difference of 30 degrees between active and passive range of motion measurements. A combination of these phenomena may explain the observed inflexibility in changing the grip type. Note, however, that she was able to adopt an alternative grip type (i.e., frontal grip, see Figure 1) as was ensured before the experiment.

Collectively, these results indicate that all three hemiparetic participants tended to persevere in a previously adopted task solution to a larger degree than the ‘typical’ control participant, pointing to a more inflexible grip selection process than the ‘typical’ control participant.

As regards anticipatory movement planning, again, clear differences between the ‘typical’ control participants and the three hemiparetic participants were found. For the ‘typical’ control participant, the two task goals had distinctive effects on the position of the switch points. Specifically, a hysteresis region was present in the rotation condition but absent in the lift condition. In the lift condition, the hand orientation with which the object was grasped remained (approximately) the same during lifting, whereas in the rotating condition the hand orientation was required to change constantly. Therefore, attaining a comfortable hand orientation upon grasping the object was considered more demanding in the lifting condition than in the rotating condition. The lack of a hysteresis effect in the lift condition exemplifies that the particular grip chosen by the ‘typical’ control participant is driven by the need to attain a comfortable hand orientation when grasping the object in this condition. At the same time, it implies a process of forward planning in which the goal of the task is already taken into account when grasping an object (cf. Rosenbaum et al., 1992). The presence of a hysteresis region in the rotation condition is understandable from this perspective, due to the decreased need to attain a comfortable hand orientation in the rotation condition.

The three hemiparetic participants were insensitive to task goals at the level of anticipatory grip planning. For participants CV and LC a hysteresis region was present in both conditions, whereas it was absent in both conditions for participant GV. These results demonstrate a lack of sensitivity for task-goal requirements at the level of anticipatory grip selection in these participants. In a recent study of Steenbergen, Hulstijn et al. (2000), it was
shown that children with spastic hemiparesis probably do not plan for comfortable end postures with their affected hand. The present results corroborate these findings and indicate that the adopted grasping pattern is primarily based on the previously adopted grasping pattern, instead of flexibly tuned to the new task configuration. This suggests that hemiparetic participants CV, LC, and GV use a step-by-step control strategy, in which one movement is planned at a time. Wu, Trombly, Lin, & Tickle-Degnen (1998) suggested that past experience may help produce an internal representation of the relationship between person and object, thereby diminishing the neuromotor problems of the affected arm of patients after cerebrovascular accident (CVA). A similar reasoning might apply for the three hemiparetic participants in this study, where the most affected hemiparetic participant (i.e., the largest neuromotor problems), GV, relied most on past experience.

Movement execution

As regards movement execution, for the ‘typical’ control participant, both peak velocity and peak grip aperture occurred earlier in the lift condition than in the rotation condition. These findings are in line with Marteniuk et al. (1987, 1990) and our expectations that, given the larger precision requirements for lifting the object as opposed to rotating it, peak velocity and peak aperture are attained earlier in the movement. Hence, precision requirements of the task are reflected in the kinematics of the reaching phase. Similar effects of task goal on reach kinematics were found for hemiparetic participants CV and LC (for comparable findings regarding grip aperture in children with spastic cerebral palsy, see Cope and Trombly, 1998). The fact that hemiparetic participants CV and LC demonstrated sensitivity for the task goal demands at the level of reach kinematics was surprising, given that they did not display such sensitivity at the level of (anticipatory) grip selection. It therefore seems that a dissociation exists between higher level action planning, as reflected by (anticipatory) grip selection, and lower level action execution, as reflected by the reach kinematics of these two participants. Such a dissociation has also been found in a study by Hermsdörfer, Laimgruber, Kerkhoff, Mai, & Goldenberg (1999), in which the prehension movements of the ipsilesional arm of participants with left brain damage were compared to those of participants with right brain damage.

As for the results on grip planning, the results on reach kinematics deviated for participant GV. The percentage of time to peak velocity did not vary as a function of task goal
and the peak grip aperture occurred later in the lift condition than in the rotation condition. The latter result suggests that for this participant grasping an object and subsequently rotating it required more precision than when it had to be lifted. An explanation for these deviant results might again been sought in the clinical evaluation (Table 2). Participant GV was the only participant that had increased spasticity levels for wrist flexion and extension (Ashworth 2 and 1, respectively). The other two participants only had increased spasticity levels at the elbow joint. In addition, participant GV displayed the largest muscle weakness at the flexors and extensors of the wrist joint as exemplified by the difference scores between passive and active range of motion measurements (Table 2). Based on these clinical evaluations it may be speculated that for participant GV it is probably more difficult to rotate the object than to lift it as rotating an object predominantly involves flexion and extension of the wrist joint.

As regards joint contribution to between-trial switches in hand orientation, for the ‘typical’ control participant, alterations in the wrist, and to a much lesser extent alterations in the shoulder, contributed to these switches. For the least affected hemiparetic participant (CV), the results were similar to that of the ‘typical’ control participant, although the contribution of the shoulder joint was larger. For the more affected hemiparetic participant LC, the shoulder joint contributed most followed by the wrist joint. It therefore appears that, compared to the ‘typical’ control participant, in these two hemiparetic participants the contribution of the more proximal movement segment (shoulder) to switches in hand orientation is increased, whereas the contribution of the more distal movement segment (wrist) decreased. Finally, as participant GV did not show any switches in hand orientation this analysis was deemed unusable.

For individuals with hemiparetic cerebral palsy, the hand and fingers are generally more affected than the trunk and shoulder (e.g., Twitchell, 1951), and within the hand a performance deterioration from index to little finger exists (e.g., Steenbergen, Verenga, Haande, & Hulstijn, 1998). Hence, there is a decline in performance in the proximal-distal direction, but also in the radial-ulnar direction. A reason for this may be that the more proximal movement segments are controlled bilaterally, whereas the more distal movement segments are controlled unilaterally (Aglioti, Berlucci, Pallini, Rossi, & Tassinari, 1993; DiStefano, Morelli, Marzi, & Berlucci, 1980; Kuypers & Brinkman, 1970). The present trend of increased proximal involvement from ‘typical’ control participant via participant CV to LC (i.e., less to more affected hemiparetic) participant, may be explained by this, and as such, can be seen as a (flexible) adaptation to their neuromotor limitations.
In the present study, we attempted to distinguish between the direct consequences of the neuromotor disorder and the potentially developed long-term adaptations to the disorder in three individual hemiparetic participants. Despite the ostensible inflexible features in especially movement planning, the participants with spastic hemiparesis did not show performance breakdowns (i.e., they were able to perform the task according to the instructions). For example, the most affected participant GV did not switch the grip pattern at all, but was still able to perform the task as required by the instruction. That no such performance breakdowns were observed might possibly be due to the functional reorganization of the movement system during the execution of the grasping movement. However, it has yet to be established whether the observed inflexibility in grip planning persists when a functional reorganization during the execution phase is not sufficient to perform the task. In future research, currently being performed in our lab, tasks need to be introduced that demand flexible switching in grip pattern to comply with the task instruction. Stated differently, if participants still persevere in using the previously adopted grip type, a ‘performance breakdown’ is expected to occur. Therefore, whether or not the movement patterns that were found in the present study should be denoted pathological or adaptive can not be answered conclusively. It was clear, however, that a dissociation between planning and execution exists in the flexibility with which task solutions are obtained. Moreover, the severity of the disorder is associated with both inflexibility and the dissociation between both levels. While inflexibility was shown for grip planning in all three participants, the two least severely affected participants were flexible at the movement execution level. The most severely affected participant appears (partially) to lack this flexibility even at movement execution level.
Chapter 3

Anticipatory planning deficits and context effect in hemiparetic cerebral palsy
Abstract

Individuals with hemiparetic cerebral palsy (HCP) display deviant motor output, predominantly on one side of the body. The question pursued here is whether HCP participants have the ability to anticipate the forthcoming perceptual-motor demands of the goal of an action sequence. Such anticipatory planning was necessary to successfully perform the tasks that were studied. In experiment I, HCP participants had to grasp a hexagonal knob with their unaffected hand by choosing one of five possible grasping patterns (free choice) and consequently rotate it 60°, 120°, or 180° Clockwise or Counterclockwise. HCP participants showed a large amount of task failures that were persistent throughout the task. These findings suggest a deficit in anticipatory planning. No such task failures were observed for the control group. In addition, the instructed degree of rotation had less effect on the selected grasping pattern for the HCP participants than for the controls. In experiment II, we investigated if HCP participants are prone to use context information that is directly available in the task, instead of planning the forthcoming perceptual-motor demands. To that aim, an arrow was inserted at one of the sides of the hexagon in a position that had no relevance for the action to be planned and executed. The location of this arrow significantly affected the grip selected in the HCP participants, but not in controls. Overall, the results suggest an anticipatory planning deficit in HCP participants that may be caused by an impairment at the motor imagery level. Consequently, as an alternative strategy, performance in HCP participants was predominantly based on information directly available in the task context.

Based on:
When an object is grasped, the selection of an appropriate grip is critically dependent on the subsequent action that needs to be performed with the object. For example, it was repeatedly shown that a cup that is placed upside down is grasped with a grip that leads to a comfortable posture at the end of the task, viz. when the cup is turned over (end state comfort effect, Elsinger & Rosenbaum, 2003; Rosenbaum, Engelbrecht, Bushe, Loukopolous, 1993; Rosenbaum & Jorgenson, 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993; Short & Caraugh, 1997, 1999). This finding suggests that proper grip planning demands an ability to go beyond immediately available perceptual information and take into account the forthcoming perceptual-motor demands associated with the goal of the action sequence (Johnson-Frey, McCarty, & Keen, 2004). In the remainder of the article we will refer to this process as anticipatory planning.

The motor output at the contralesional side of individuals with spastic hemiparesis as a result of cerebral palsy (HCP) – the group under investigation in the present study – deviates from that of healthy individuals (for evidence on ipsilesional deviations, see Steenbergen, Meulenkoek, & Rosenbaum, 2004). In general, CP originates from a brain trauma (often a lack of oxygen to the immature brain cells) around birth. The damaged brain areas in cerebral palsy usually include the corticospinal tract and the thalamus/basal ganglia (Forssberg, 1999). Corticospinal damage generally leads to spasticity - an overall increase in muscle tone and a velocity-dependent increase of tonic reflexes - and impaired dexterity. Thalamus/basal ganglia damage is associated with dyskinesia and athetosis (Cruickshank, 1976; Duque, Thonnard, Vandermeeren, Sébire, Cosnard, & Olivier, 2003). Dyskinesia is reflected in difficulties or distortions in performing voluntary movements, and athetosis is characterized as a general slowing of voluntary movements. About two-thirds of the fibers of the corticospinal tract originate in the motor cortex, whereas the vast majority of the remaining one-third of the fibers of the corticospinal tract originates in the somatosensory cortex (Bear, Conners, & Paradiso, 2001).

As the primary motor cortex plays a crucial role in the execution of movements, it is not surprising that many studies on HCP report various deviations in movement output at the contralesional side. Among these deviations are slower movements that consist of more submovements (Chang, Wu, Wu, & Su, 2005; Trombly, 1992, 1993; Utley & Sugden, 1998), more variable hand trajectories (Thiel van, Meulenkoek, Smeets, & Hulstijn, 2002), inappropriate force levels in the hand and fingers (Eliasson, Gordon, & Forssberg, 1991, 1992), a stereotyped shoulder-elbow recruitment order (Steenbergen, van Thiel, Hulstijn, &
Meulenbroek, 2000), and increased levels of trunk involvement (Roon van, Meulenbroek, & Steenbergen, 2004).

However, recent behavioral findings in HCP suggest deviations at the level of movement planning as well (Mutsaarts, Steenbergen, & Bekkering, 2005; Mutsaarts, Steenbergen, & Meulenbroek, 2004; Steenbergen, Meulenbroek, & Rosenbaum, 2004; Steenbergen & Kamp van der, 2004). How well is this understandable from damage to the corticospinal tract? The premotor area and the supplementary motor area, together with the dorsolateral prefrontal cortex (located immediately anterior to the premotor cortex) are generally thought to be involved in movement planning (Rizzolatti, Fogassi, & Galese, 2002). The dorsolateral prefrontal cortex, at the top of the cortical perception-action hierarchy, appears to play a major role in the planning and execution of more broad and complex goal directed actions, often involving movement sequencing (e.g., Fuster, 2000). Under the assumption that movement planning precedes movement execution, we studied the behavioral deviations at the ‘higher’ planning level to understand its contribution to the deviations in motor output of individuals with HCP. Although the present study is behavioral in nature, we believe the results may provide a basis for speculation on the neural mechanisms underlying this behavior.

A recent study by Mutsaarts et al. (2004) suggests that individuals with HCP do not use anticipatory planning when grasping an object (see also Mutsaarts et al., 2005; Steenbergen et al., 2004, Steenbergen & Kamp van der, 2004). In that study, participants were asked to repeatedly grasp a cubical object of which the location was gradually changed. After having grasped the object, participants either lifted it or rotated it back-and-forth. The HCP participants selected a grip that was predominantly affected by the grip that was used in a previous trial. Thus, their grip was not flexibly adapted to the changing task context, as was found in controls. Occasionally, this task solution led to grasping patterns that involved extreme pronation or supination of the wrist joint. Despite this ostensible awkward task solution the HCP participants were still able to comply with the task instruction, that is, grasp the cube and subsequently lift or rotate it. Therefore, this deviant grip planning behavior may reflect an adaptation to the disorder, instead of being indicative of the disorder as such (cf. Latash & Anson, 1996). The design of the present study allows us to make a more definite distinction between adaptation and disorder. Conditions are introduced in which participants are not able to successfully perform the task according to task instructions if they do not select a proper grip. If such behavior would occur, that is, a failure to perform the task, it is indicative of a deficit in planning instead of being adaptive.
The present study consisted of two experiments. The aim of experiment I was to find out whether HCP participants are able to go beyond immediately available perceptual information and anticipate the forthcoming perceptual-motor demands of the goal of an action sequence. We designed a task in which a particular grasping pattern needs to be selected on the basis of such anticipatory planning in order to perform the task successfully.

As previous studies indicated that participants with HCP generally do not use anticipatory planning, the question arises as to what information they in fact use for grip planning. The results of the studies by Steenbergen, Hulstijn et al. (2000) and Steenbergen et al. (2004) showed that participants with HCP do not select a grip that would lead to a comfortable hand posture at the end of the grasping sequence, as would be the case when they use anticipatory planning. Instead, they selected a grip that led to a comfortable posture at the start of the grasping sequence. Based on this finding we hypothesize that participants with HCP may use information directly available in the task context for grip planning, rather than to anticipate forthcoming perceptual-motor demands. This hypothesis was tested in experiment II. Participants had to perform the same task as in experiment I, but we manipulated the informational content of the task.

Method

Participants

11 adolescents with spastic hemiparetic cerebral palsy (4 with left spastic hemiparesis and 7 with right spastic hemiparesis, mean age 16.8 years, SD 1.4 years) and 11 neurologically healthy control participants (3 left-handed and 8 right-handed, mean age 20.2 years, SD 2.7 years) participated in the experiment on a voluntary basis. At the moment of testing, the hemiparetic participants were students from the Werkenrode Institute (Groesbeek, The Netherlands) where they followed an adapted educational program. They were selected based on being diagnosed as having spastic hemiparesis due to cerebral palsy (HCP). Because of the fact that they were students of a school, instead of patients in a medical clinic, only limited information on individual neuropathology was available. Additional information on the HCP participants is given in Table 1. The control group consisted of psychology students from the Radboud University in Nijmegen who participated as part of a college research credit requirement.
All participants signed an informed consent prior to testing. This study has been approved by the local ethics committee and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

To characterize the participants in terms of gross hand function of the type studied here, we administered the Box and Block test (Mathiowetz, Volland, Kashman, & Weber, 1985) according to the instructions in the

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test-protocols (see also Table 1). The test-retest reliability at six-month intervals of the Box and Block test has been reported as rho coefficients of .937 and .976 for the left and right hand, respectively. Furthermore, we also report the results of the Dutch version of the Wechsler Intelligence Scale for Children – Revised (WISC-R; Wechsler, 1974) (see also Table 1). Since we tested the performance of the unaffected hand on a motor planning task, we were particularly interested in the results of one subtest of the Performance section of the WISC-R, namely Mazes. According to the test instruction, the scores on this particular subtest indicate the capacity for
graphomotor planning, visual motor coordination and speed. The reliability coefficients for this subtest have been reported as $\lambda = 0.73$.

![Image of apparatus](image.png)

*Figure 1. Photograph of the custom made apparatus. It consists of a metal platform with a wooden disk attached on top. At the center of the disk a plastic hexagonal knob is placed. At each of the six sides of the hexagon an arrow is inserted. Each of these arrows is pointing to one of a total of six LED's.*

**Experimental set-up and apparatus**

The participants were comfortably seated on an ergonomic chair positioned in front of a table at the level of the abdomen. On this table a custom made apparatus was placed. It consisted of a metal platform (measuring 32 cm in length and 24 cm in width), with a wooden disk (measuring 40 cm in diameter) attached on top (see Figure 1). The disk could be tilted at a slope between $0^\circ$ and $90^\circ$ relative to the platform. A plastic hexagonal knob (measuring 11 cm in diameter and 6 cm in depth) was placed at the center of the disk. The hexagon could rotate around its vertical axis with only limited friction. At each of the six sides of the hexagon an arrow could be inserted (measuring 15 cm in length and 0.5 cm in width). At 0.5 cm from the edge of the disk 6 LEDs (Light Emitting Diodes) were placed, at $0^\circ$, $60^\circ$, $120^\circ$, $180^\circ$, $240^\circ$, and $300^\circ$ (see Figure 1).

A digital camcorder was used to record the performance of the participants during the experiment. For privacy reasons the head of the participants was not recorded.
Design and procedure

The study consisted of two experiments. During the practice sessions that took place prior to the start of the experiments, crucial adjustments were performed by the experimenter. They consisted of adjusting the slope of the disk and adjusting the distance of the apparatus to the front edge of the table to each participant’s active range of motion. This resulted in slopes ranging from 60° to 80° and distances ranging from 9 to 22 cm. These adjustments were made to ensure that for each participant the same five distinct grasping patterns were possible, and at the same time grasping pattern 6 was biomechanically impossible (see Figure 2a and b). For each grasping pattern the thumb and the fingers were placed on opposite sides of the hexagon. As shown in Figure 2 b, and assured prior to the experiment, grasping pattern 6 did not meet these requirements. Grasping patterns 1:5 were defined by the position of the fingers (see Figure 2a and b). The participants used the practice sessions to find a comfortable sitting posture that they were asked to maintain during the experiment. Furthermore, they familiarized themselves with the five possible grasping patterns. On average, practice sessions took about 10 minutes, including adjustments and instructions.

In both experiments the procedure was similar. As a prescribed starting posture, participants placed their dominant hand (palm facing down) in front of them on the tabletop. Each trial started with an instruction to rotate the hexagon 60°, 120°, or 180° clockwise (Cw) or 60°, 120°, or 180° counterclockwise (Ccw). On the basis of this instruction, participants could select one of the five possible grasping patterns (free choice) so that the task could be performed. In a control condition, participants were asked to grasp the hexagon without rotating (WR) it, to establish a baseline measure of the ‘preferred’ grasping pattern. Hence, there were a total of seven different tasks that participants had to perform upon grasping the hexagon. Importantly, some specific combinations of grasping pattern and instruction would lead to unsuccessful task completion (in the remainder of the text we will use the term ‘task failure’ to indicate such an event). For example, for the combination of instruction to rotate the hexagon 180° Cw and the selection of grasping pattern 3, the fingers would end at position 6 and the thumb would end at position 3. As can be seen in Figure 2b, this was biomechanically impossible.

A note on the instruction. As HCP participants had reduced verbal abilities (see Table 2), we kept verbal instruction as simple as possible. Prior to each trial, we instructed the participants to grasp the hexagon with one of the five possible grasping patterns and rotate it either one, two, or three ‘units’ (1 unit = 60°) clockwise or counterclockwise. As the angular distance between two successive LEDs on the disk corresponded to 60°, the position of the
arrow(s) in relation to the position of the LEDs provided direct visual feedback about the
degree to which the hexagon was rotated. Moreover, each time the hexagon was rotated 60°
(or a multiple of 60°) a short – computer generated – beep sounded, to provide auditory
feedback about the degree to which the hexagon was rotated. Since all participants performed
the task according to task instructions, we are confident that the results obtained can not be
attributed to a lack of comprehension of the task.

In experiment I, an arrow was inserted at each of the six sides of the hexagon. Participants performed 35 trials in this experiment, determined by 7 instructions * 5 replications. The trials were presented in a randomized order. In experiment II, only one arrow was inserted; at position 1, 2, or 3 in Cw trials and at position 3, 4, or 5 in Ccw trials (see Figure 2a). This position of this arrow had no significance for the planning and execution of the task. Participants performed 95 trials in this experiment, determined by 6 instructions (60°, 120°, and 180° Cw and Ccw) * 3 arrow positions * 5 replications and the additional 5 WR trials for arrow positions 1 to 5. As in experiment I, the trials were presented in a randomized order. No explanation as regards the changing task context between both experiments (one arrow vs. six arrows) was given to the participants.

Figure 2a. The hexagon with the numbers indicating the 6 different sides. b. The 5 possible grasping patterns (numbers 1:5). Number 6a and 6b represent grasping pattern 6. As is visible from the picture, this grasping pattern is biomechanically impossible, as the thumb is not able to reach the hexagon.
Of the participants with spastic hemiparesis, five started with experiment I (two with left hemiparesis and three with right hemiparesis) and six started with experiment II (two with left hemiparesis and four with right hemiparesis). Of the control participants, five started with experiment I and six started with experiment II.

Data analyses

The grasping patterns that were adopted were scored off-line via analysis of the video-records. Specifically, grasping patterns were categorized by determining the position of the fingers at the moment of grasping the hexagon. This resulted in five grasping patterns ranging in number from 1 to 5 (see Figure 2a and b).

Statistical analysis

To test the effects of the manipulation of instruction and the position(s) of the arrow(s) on the grasping pattern distribution for both groups, we used loglinear procedures. Furthermore, we calculated Spearman rank correlation coefficients \( r_s \) to statistically analyze the relation between the amount of performance failures for each participant with HCP on the one hand and the individual scores on the Box and Block test and the WISC-R scores on the other (see Table 2). Of these latter scores, we were particularly interested in the Mazes subtest, which according to the test protocol in part reflects graphomotor planning.

Table 2

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Notes. BBT/i: Box and Block test for the affected hand; BBT/u: Box and Block test for the unaffected hand (u). *Correlation is significant at the .05 level (2-tailed).
Results

Experiment I: effect of instructed rotation

In Figure 3, the distribution of grasping patterns averaged per group is shown. The length of the bars depicts the number of grasps at that particular side of the hexagon, averaged per group. Both the control group and the HCP group strongly prefer grasping pattern 3 when taking hold of the hexagon in the Without Rotation (WR) instruction. This is reflected by the large bars at position 3 in the WR hexagons in Figure 3. As indicated by the hatched bars, the Cw 180° and Ccw 180° instructions elicited a substantial amount of task failures (21 and 23 out of 55 trials, respectively) for the HCP group. In other words, in these trials the rotation task could not be successfully performed due to an erroneous grasping pattern selection. In contrast, the control group showed no task failures. Finally, for the control group, the larger the instructed rotation (60° → 120° → 180°, both Cw and Ccw) the more the observed grasping patterns deviated from the preferred grasping pattern 3. This systematic trend was much smaller for the HCP group. A loglinear analysis with the factors Group (2 levels), Instruction (7 levels), and Grasping pattern (5 levels) showed a significant three-way interaction effect ($\chi^2(24) = 98.66, p<0.001$). This means that the effect of instruction on the grasping pattern distribution differed significantly between the groups. Step down analyses of this interaction showed that for both the control group ($\chi^2(24) = 789.05, p<0.001$) and the HCP group ($\chi^2(24) = 239.45, p<0.001$) an effect of instruction on the grasping pattern distribution existed, although this effect was much smaller for the HCP group.

Experiment II: effect of arrow position

In Figure 4 the Ccw 180° instruction is shown for experiment I and for the three arrow positions of experiment II (for data on all six rotation instructions for experiment II, see Table 3A and B). The arrow in each hexagon indicates the position of the arrow in experiment II. The length of the bars depicts the number of grasps at that particular side of the hexagon, averaged per group. It is clear from Figure 4 and Table 3B that for the HCP group the position of the arrow had a large influence on the grip selected, as shown by the large bars at these arrow positions. In contrast, for the control group, no such trend was observed (see Figure 4 and Table 3A). We performed a loglinear analysis with the factors Group (2 levels), Arrow (2 levels: 1 arrow or 6 arrows), and Grasping pattern (5 levels) to determine whether the position(s) of the arrow(s) had a differential effect on the grasping pattern distribution for the HCP group and the control group. We found a significant three-way interaction ($\chi^2(4) =
19.47, $p<0.001$), indicating that the influence of the position(s) of the arrow(s) on the adopted grasping pattern was different for both groups. Step down analyses of this interaction revealed a significant arrow effect on the grasping pattern distribution for the HCP group ($\chi^2(4) = 29.59, p<0.001$) but not for the control group ($\chi^2(4) = 1.51, p=ns$). Hence, contrary to the control group, the grasping pattern of the HCP group was affected by the position of the arrow.

Control participants

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Hemiparetic participants

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<td>Ccw 180°</td>
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Figure 3. Grasping pattern distribution for the different rotation instructions in experiment I. The length of the bars depicts the number of grasps at that particular side of the hexagon. The top 7 hexagons display the results for the control group and the 7 hexagons at the bottom display the results for the HCP group. The total number of trials per instruction is 55. The hatched bars indicate task failures.
Table 3a
*Number of Occurrences of the Grasping Patterns in Experiment II for the Control Participants. All Rotation Instructions for Arrow Position 1 to 5 are Presented*

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*Note. A * indicates task failures.*

Table 3b
*Number of Occurrences of the Grasping Patterns in Experiment II for the Hemiparetic Participants. All Rotation Instructions for Arrow Position 1 to 5 are Presented*

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*Note. A * indicates task failures.*
For the HCP group, we also tested whether the significant arrow effect was present both in trials in which the arrow was inserted at positions further away from the ‘preferred’ grasping pattern (positions 1, 2, 4, and 5), and in trials in which the arrow was inserted at position 3, the ‘preferred’ position (as assessed in experiment I). A loglinear analysis in which the grasping pattern distribution of experiment I was compared with the grasping pattern distribution for arrow position 1, 2, 4, and 5 of experiment II showed a significant arrow effect ($\chi^2(4) = 79.17, p < 0.001$), as did the analysis in which the grasping pattern distribution of experiment I was compared with the grasping pattern distribution for arrow position 3 of experiment II ($\chi^2(4) = 15.63, p < 0.01$). Hence, the grasping pattern distribution of the HCP group was affected by the position of the arrow, both at ‘preferred’ and ‘unpreferred’ arrow positions.

**Anticipatory planning deficits and clinical measures**

Table 1 shows the number of task failures summated for both experiments and the scores on the clinical measures (Box and Block test scores and scores on the Wechsler Intelligence Scale for Children – Revised; Wechsler 1974) for the HCP participants. We calculated Spearman rank correlation coefficients to establish the possible relation between the amount of task failures on the one hand, and the Box and Block test scores and the WISC-R scores on the other. We found significant negative correlations between Failures and Mazes, Failures and Picture Completion, Failures and Information, and Failures and Vocabulary, respectively. Moreover, we found significant negative correlations between Failures and Verbal IQ and Failures and Total IQ, but not for the number of task failures and the scores on the Box and Block test for the affected and unaffected hand (see Table 2).

Control participants
Hemiparetic participants

![Figure 4. Grasping pattern distribution for the Ccw 180° rotation instruction in experiment I and in experiment II, with arrow position 3, 4, and 5. The top 4 hexagons display the results of the control group and the 4 hexagons at the bottom display the results of the HCP group. The arrow in each hexagon indicates the position of the arrow in experiment II. The length of the bars depicts the number of grasps at that particular side of the hexagon. The total number of trials per instruction/arrow position is 55. The bars with the dotted pattern indicate task failures.](image)

**Discussion**

The goal of the present study was twofold. First, we examined whether HCP individuals have the ability to anticipate the forthcoming perceptual-motor demands of the goal of an action sequence (experiment I) when planning a grip. Second, we examined whether they are prone to use directly available task context information in such a task (experiment II). The task was designed in such a way that anticipatory planning was a prerequisite to successfully perform the task.

Because HCP is primarily considered to be a movement disorder, one could argue that the findings of the present study (in part) reflect deficits at the level of movement execution. There are three reasons that falsify this argument. First, the HCP participants performed the task with their unaffected hand, which is relatively unaffected. Second, we ensured prior to the experiments that each participant was biomechanically able to use all task solutions. Indeed, because of the alternating position of the arrow between trials in experiment II, each HCP participant used all five possible grasping patterns. Third, the Box and Block test (Mathiowetz et al., 1985) we administered to assess manual dexterity showed no correlation with the amount of task failures. Given these reasons, we believe that the results obtained are unlikely to be the consequence of deficits at the movement execution level. Instead, they may be attributed to the antecedent movement planning level.
Anticipatory planning deficit

In experiment I, we showed that the rotation instruction had less effect on the grasping pattern selection for the HCP participants than for the control group. This result indicates anticipatory planning deviations in HCP participants that are comparable with those previously reported (Mutsaarts et al., 2004, 2005; Steenbergen et al., 2004; Steenbergen, Hulstijn et al., 2000). However, in the present study anticipatory planning was a prerequisite for successful task completion in some conditions. As such, we have excluded the possibility that individuals with HCP can use anticipatory planning, but nonetheless prefer to use an ‘alternative’ planning strategy. Therefore, we conclude that individuals with HCP have an anticipatory planning deficit.

Possible underlying cognitive and neurophysiological mechanisms involved in anticipatory planning are provided by the imagery as planning theory (Johnson, 2000b). This theory assumes that anticipatory planning consists of the mental transformation of a somatomotor representation of the effector system, in order to select a proper response (see also Parsons, 2003). For the present task, this implies that participants have to mentally rotate a somatomotor representation of their (grasping) hand. Several studies indicate that a distinct neural mechanism underlies such mental transformation of body parts, generally referred to as motor imagery (e.g., Sirigu & Duhamel, 2001; Tomasino, Rumiati, & Umilta, 2003). Given the relatively small effect of rotation instruction on the selection of the initial grasping pattern and especially the high number of task failures, it might be suggested that individuals with HCP are not able to properly perform such mental transformations, hence have a motor imagery deficit. This suggestion is corroborated by the significant negative correlation between the number of failures - which served as the prime indicator of the anticipatory planning deficit - and the scores on the Mazes subtest of the WISC-R intelligence test (Wechsler, 1974), which is specifically designed to test graphomotor planning. In the Mazes task participants are presented with a drawing of a maze. They are instructed to first mentally simulate the drawing of the correct path through the maze, and subsequently to draw the response. Hence, the first part of the Mazes task requires one to perform mental transformations comparable to those of the imagery as planning theory.

Is this hypothesized motor imagery deficit reflected by the consistent involvement of one or more brain structures across the HCP participants, or might there be a more functional cause? For instance, one might consider the possibility that given their neuromotor limitations, individuals with cerebral palsy lack the typical motor experience required to properly develop representations that enable motor imagery. Since the HCP participants in the
present study have neuromotor limitations predominantly on one side of the body, this latter possibility is somewhat unlikely. Especially because they used the relatively unaffected hand in the present study, with which they have had much motor experience. How well then is the motor imagery deficit hypothesis understandable given the specific brain structures damaged in individuals with HCP? The brain areas that are found to be activated during motor imagery include the cerebellum, premotor area, supplementary motor area, posterior parietal cortex (Decety et al., 1994; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Lang et al., 1994; Lang, Cheyne, Hollinger, Gerschkager, & Lindinger, 1996; Parsons et al., 1995; Parsons & Fox, 1998; Rao et al., 1993; Stephan et al., 1995; Wolbert, Weiller, & Büchel, 2003), and possibly even the primary motor cortex (Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Kosslyn et al.; Porro et al., 1996; but see Parsons et al.; Sirigu et al., 1996). Wolbert et al. hypothesized that the role of the parietal cortex in motor imagery is to evaluate the imagined motor performance by comparing reafferent signals from the prefrontal motor areas with stored internal representations of motor plans (see also Crammond, 1997). Recent findings of Johnson, Rotte, Grafton, Hinrichs, Gazzaniga, and Heinze (2002) are in line with this hypothesis. They showed that a distinct parietofrontal circuit is activated in imagined grip selection, including the bilateral dorsal premotor cortex, contralateral intraparietal sulcus, and right superior parietal lobule. Also, Johnson (2000b) showed that only in cases where the right posterior parietal and left frontal regions where spared, hemiparetic individuals due to a CVA retain the ability to accurately represent prehensile movements that involve the affected limb (see also Johnson, Spreh, & Saykin, 2002). It thus seems that the brain areas responsible for motor imagery largely overlap the damaged brain areas in individuals with HCP.

Although the motor imagery deficit hypothesis appears readily testable, recent patient studies show that the typical paradigm used for testing motor imagery (i.e., the mental rotation of pictures of hands) might produce interpretation problems, especially when neurologically impaired populations are involved. In an fMRI study, Lange de et al. (2004) compared performance of both a visual imagery task (mentally rotating a typographical character) and a motor imagery task (mentally rotating a picture of a hand) between control participants and participants with chronic fatigue syndrome (CFS). Except for a general slowing of the CFS group, they did not find behavioral differences between both groups. This would indicate that motor imagery is preserved in the CFS group. However, the fMRI data showed that in the motor imagery task, the CFS participants actually employed a visual strategy rather than a motor strategy. Similarly, Tomasino and Rumiati (2004) showed that patients with unilateral brain damage used either a motor or a visual strategy depending on the
location of the brain damage. Hence, a more conclusive answer to our suggestion that an 
impairment at the level of motor imagery lies as the basis of the established anticipatory 
planning deficit in individuals with HCP will require an elaboration of the typical motor 
imagery paradigm to rule out possible alternative strategies used in such tasks.

**Context effects**

In experiment II, we examined the effect of task context on the grip selection process. 
We reasoned that if the HCP individuals indeed have an anticipatory planning deficit, it might 
be that they base their choice of grip selection on the directly available task context 
information. Effects of task context on the kinematics of prehensile movements have been 
frequently reported in healthy participants (Lin, Tang, Chen, Wu, & Chen, 2001; Marteniuk, 
MacKenzie, Jeannerod, Athenes, & Dugas, 1987) and in participants within a broad spectrum 
of movement disorders, such as spasticity resulting from a cerebro vascular accident 
(Trombly & Wu, 1998; Wu, Trombly, & Lin, 1994; Wu, Trombly, Lin, & Tickle-Degnen, 
and spasticity resulting from CP (Volman, Wijnroks, & Vermeer, 2002; Weel van der, Meer 
van der, & Lee, 1991). In a recent study, Steenbergen et al. (2004) showed an effect of task 
context on grip planning in participants with HCP that differed among left- and right sided 
brain damage. More in general, these studies showed that the performance at the level of 
movement execution (such as smoothness of moving and movement speed) and at the level 
of movement planning (the selection of an appropriate grip) improved dramatically when (1) the 
tasks were performed in a more functionally relevant/natural setting, and (2) the to-be-grasped 
object was available instead of based on imagery alone. Note that in all these studies, the 
motor output in a more ‘poor’ (non-functional/object absent) context was compared with the 
motor output in a more ‘rich’ context (functional/object present).

However, in experiment II we did not introduce a poor/rich dichotomy in context 
information. Instead, we included only one arrow at different sides of the hexagon, thereby 
leaving the context neutral across conditions. We reasoned that if the arrow was placed only 
at positions that ensured successful task solutions, interpretation of the results would remain 
ambiguous. If participants consistently grasped the hexagon at the position of the arrow, this 
could either imply that they focus solely on the task context information, or that this 
information somehow facilitates the anticipation of the perceptual-motor demands of the goal 
of the action sequence. Therefore, we ensured that using the arrow in guiding the grip 
selection would result in a task failure in one-third of the 180° rotation instruction trails.
Consistent with our hypothesis, for HCP participants the grip selected was indeed influenced significantly by the position of the arrow, while this was not the case for the controls. Importantly, this was also the case when it would lead to task failures. Hence, it seems that HCP individuals are prone to predominantly use visual information directly available in the task context for selecting a grip, instead of going beyond such information by taking into account the forthcoming perceptual-motor demands associated with the goal of the action sequence.

Clinical measures

Next to the Mazes subtest (as discussed above), we also found significant correlations between the number of task failures and the WISC-R subtests Picture Completion, Information, and Vocabulary. The latter two subtests are part of the (also significantly correlated) Verbal IQ part of the WISC-R. It may be argued that the performance of the HCP participants in the present study reflects a lack of comprehending the verbal instruction, or difficulties with remembering the verbal instruction. In the first experiment, the verbal instruction consisted of two parts that were related to the required direction of rotation (clockwise or counterclockwise) and to the required degree of rotation (60°, 120°, or 180°). In the second experiment, the verbal instruction was similar, but potentially, the arrow may have provided an additional implicit instruction (‘ignore the arrow’). The results showed that the instructed direction of rotation indeed affected the grasping pattern, as instructions to move the hexagon clockwise led to grasping it at the left side and vice versa (see Figure 3b). For the instructed degree of rotation no such effect was apparent, as participants did not deviate more from the preferred grasping pattern when larger degrees of rotation were required than when smaller degrees of rotation were required. However, the latter result does not mean that participants did not comply with this part of the instruction, because in all trials they rotated the hexagon to the degree that was instructed. More specifically, they understood the instruction and acted accordingly, but both parts of the task instruction had differential effects on their initial grasping pattern, indicating a specific deficit in anticipatory planning. Furthermore, the results presented here are in line with anticipatory planning deviations found in comparable tasks in HCP (Mutsaarts et al., 2004, 2005; Steenbergen et al., 2000, 2004; Steenbergen & Kamp van der, 2004). These studies used either very limited verbal instruction or direct visual cueing (Mutsaarts et al., 2005). Taken collectively, we deem it unlikely that the reduced verbal IQ of the HCP participants, and the supposed difficulties to understand task instruction, underlies the findings of the present study. Conclusive empirical evidence in
support of this reasoning could be provided via examination of an age-matched control group with similar verbal abilities as the HCP group in the present study, but without motor impairments. As a possible explanation for the correlation between the verbal IQ tasks and the number of task failures, we refer to the possibility that the participants who performed poorly in the present experiments are those who probably suffered the greatest damage to brain areas involved in motor planning. It is therefore likely that these participants have more extensive damage in neighboring areas in the brain as well, such as for example Broca’s area. The proximity of this language center and the motor planning centers might explain the ostensible ‘unrelated’ correlations (Rizzolatti & Arbib, 1998).

Repeated errors

A recent study of Mutsaarts et al. (2004) showed behavioral perseverance at the level of grip selection in three adolescents with HCP. The task consisted of repeatedly grasping a square object of which the position was gradually changed leftwards or rightwards. Whereas control participants flexibly switched between the two possible grasping patterns in relation to the changing task context, the HCP participants appeared to persevere in a once chosen task solution. Although this behavior led to ostensibly awkward movement postures, it did not lead to task failures. In the present study however, in both experiments each HCP participant grasped the hexagon in such a way that it led to task failures. Importantly, similar to the Mutsaarts et al. study, these erroneous responses occurred repeatedly. Hence, instead of adjusting their behavior on the basis of the obvious negative outcome of a previous trial, the HCP participants persevered in selecting a grasping pattern that would lead to a task failure upon task completion.

Since the first reports on human error detection and correction in the 1960s (Rabbitt, 1966a, 1966b, 1967, 1968), it has been frequently shown that neurologically healthy individuals are able to detect an erroneous response and will subsequently adjust there behavior to prevent the same error from occurring again. Based on the contrast of this general finding of behavioral adjustments following errors in neurologically healthy individuals with the repetition of obvious erroneous responses in the HCP participants in the present study and the Mutsaarts et al. (2004), it would be interesting to further investigate error monitoring processes in individuals with HCP.
Summary

In sum, by presenting HCP participants and control participants with a task that required anticipatory planning to successfully perform it, we have uncovered an anticipatory planning deficit for the HCP participants, possibly due to problems at the level of motor imagery. Next, by systematically manipulating the task context, we have shown that the HCP participants are predominantly influenced by information directly available in the task context for the selection of a grip.
Chapter 4

Anticipatory planning of movement sequences in Hemiparetic Cerebral Palsy
Abstract
Anticipatory planning was examined in detail for a complex object manipulation task in individuals with Hemiparetic Cerebral Palsy (HCP), by capitalizing on the complexity and number of elements in movement sequences. Participants had to grasp a hexagonal knob using one of five possible grasping patterns following a starting cue, and sometimes, they had to rotate it subsequently either 60° or 120° clockwise or counterclockwise. The HCP participants appeared to anticipate the comfort of the different grasping patterns before movement onset. However, when the task consisted of more than one movement part, they did not complete their planning processes before movement onset. Instead, they seemed to plan the latter parts as the movement unfolds. The results are discussed in the light of possible capacity limitations of an internal model for grip selection, and a recent model on the planning and on-line control of movement performance.

Based on:
Anticipatory planning of movement sequences

Typical and defining features of cerebral palsy (CP) are disorders in motor function, that is, difficulties in the execution of movements (Ingram, 1966). Frequently, CP results in spasticity, that is, a velocity dependent increase in tonic reflexes resulting in an excessive and awkward activation of skeletal muscles (Barnes, Mclellan, & Sutton, 1994; Lance, 1980; Sanger, Delgado, Gaebler-Spira, Hallet, & Mink, 2003). In the case of hemiparetic cerebral palsy (HCP) it is especially at the contralesional body side where the deviations in motor output can be observed. Movements are characterized by increases in: number of submovements (e.g., Chang, Wu, Wu, & Su, 2005; Sugden & Utley, 1995; Utley & Sugden, 1998), variability of hand trajectories (e.g., Thiel van, Meulenbroek, Smeets, & Hulstijn, 2000; Thiel van & Steenbergen, 2001), and level of trunk involvement (e.g., van Roon, Steenbergen, & Meulenbroek, 2004). Furthermore, movements show a stereotyped shoulder-elbow recruitment order (e.g., Steenbergen, Thiel van, Hulstijn, & Meulenbroek, 2000). Finally, movement patterns are distinguished by the application of inappropriately coordinated grip and lift forces (e.g., Eliasson, Gordon, & Forssberg, 1991, 1992). Although not extensively examined, the ipsilesional body side is shown to have subtle motor deviations as well (Steenbergen, Meulenbroek, & Rosenbaum, 2004).

However, recent studies found deviations at the level of motor planning in participants with CP as well (Mutsaarts, Steenbergen, & Bekkering, submitted; Mutsaarts, Steenbergen, & Meulenbroek, 2004; Steenbergen et al., 2004; Steenbergen & Kamp van der, 2004), suggesting that part of the deviations in motor function can be attributed to disorders at the preceding motor planning level. The specific planning problems revealed by these studies reflect anticipatory planning. Anticipatory planning implies that subjects go beyond immediately available perceptual information and take into account the demands of an upcoming task during the planning of this particular task (Johnson-Frey, McCarty, & Keen, 2004).

In one study, we asked participants with HCP and control participants to grasp a square object of which the position was gradually changed leftwards or rightwards (Mutsaarts et al., 2004). The task goals consisted of either lifting the square or rotating it back-and-forth. Task goal, hence the demands of the upcoming task, significantly affected the type of grip that controls used to grasp the square. No such effect of task goal was found for grip selection of the HCP participants, indicating a lack of anticipatory planning in these subjects.

In a more recent study, we used an experimental paradigm designed to examine more explicitly the anticipatory planning process with respect to grip selection in adolescents with HCP (Mutsaarts et al., submitted). Participants were seated in front of an apparatus, consisting
of a large disk, at the centre of which a six-sided knob, a hexagon, was attached. Participants were instructed to grasp the hexagon and subsequently rotate it 0°, 60°, 120°, or 180°. The 0° rotation instruction served as a baseline measure, to establish the preferred grasping pattern. The HCP participants preferred the same grasping pattern as healthy controls in the 0° rotation task. In this grasping pattern, the arm was placed approximately in the middle range of pronation/supination, thus enabling movements in either movement direction. In other words, it reflected the most optimal choice, both functionally and biomechanically. However, when the task consisted of grasping the hexagon and consequently rotating it a certain amount, the HCP participants hardly deviated from this preferred grasping pattern in anticipation to the instructed rotation and consequent end-posture. This was the case, even when it resulted in a failure to complete the task successfully. These findings indicate a disorder at the planning level, but at the same time give a hint as to the specific nature of this planning disorder. It appeared that subjects only planned the first part of the task (viz., grasping the hexagon), instead of planning for the end of the task (viz., rotating the hexagon to a consequent end-position). These findings indicate that individuals with HCP select an initial grip that ensures a comfortable posture at the start of a movement sequence, instead of optimizing comfort of the end-posture, as is frequently shown for healthy participants (Cohen & Rosenbaum, 2004; Elsinger & Rosenbaum, 2003; Rosenbaum, Engelbrecht et al., 1993; Rosenbaum & Jorgenson, 1992; Rosenbaum, Vaughan et al., 1993; Short & Caraugh, 1997, 1999). Specifically, the findings of Mutsaarts et al. (submitted) suggest that prior to movement onset planning of the whole sequence is not complete in HCP. Hence, planning of the latter part of the movement sequence occurs during the ongoing movement, suggesting a ‘step-by-step’ planning strategy (for comparable results and reasoning, see Steenbergen & Kamp van der, 2004).

In the present study, we used a paradigm similar to Mutsaarts et al. (submitted), with the aim of examining into more detail the different phases of the planning and execution of complex prehension movements. Participants had to grasp the hexagon using a pre-instructed grasping pattern (‘forced-choice reaction time’) as quickly as possible after a starting cue (condition I), and subsequently rotate it a certain amount to a pre-instructed end position (condition II). We measured three movement parameters. First, we measured initial reaction time (time to movement onset) and second reaction time (time from touching the hexagon to start of rotation). Moreover, we also examined movement time (time from movement onset to touching the hexagon). The rationale was that if the planning processes continue after movement onset, as suggested by recent research (Mutsaarts et al., submitted; Steenbergen &
Kamp van der, 2004), this would be reflected during this first part of the execution of the movement sequence (i.e., movement time).

The major assumption underlying the experiment was that anticipatory planning is reflected in the different movement parameters, specifically in the initial reaction time measure. In two studies, Klapp (1995, 2003) suggested that two factors affect motor preparation, thus (initial) reaction time. The first factor is the internal structure of a movement part (to which he refers as a chunk). In essence, the more complex its structure, the longer it takes to prepare its motor execution, hence the longer the reaction time will be. This assumption, as first proposed by Henry and Rogers (1960), has been supported by a substantial amount of research (for an overview, see Christina, 1992). The second factor Klapp refers to is the number of connected movement parts (i.e., sequence length), where more elements demand longer preparation (Sternberg, Monsell, Knoll, & Wright, 1978; Verwey, 1994; Verwey & Eikelboom, 2003).

In the present study, we manipulated the complexity of the movement parts (i.e., chunks) in two ways. First, the pre-instructed grasping pattern was manipulated, such that comfortable and uncomfortable postures were required. The more comfortable postures were assumed to represent a less complex internal structure. The second manipulation of the complexity of the movement parts was the amount of rotation that was required for task completion. Larger rotations were assumed to reflect a more complex internal structure.

Condition I was designed to examine the effect of the comfort of the different postures on planning, that is, its effect on initial reaction time. Given that the HCP participants in the Mutsaarts et al. (submitted) study optimized this start-posture comfort, our first hypothesis was that the HCP participants in the present study anticipate posture comfort before movement onset. Hence, we predicted shorter initial reaction times for more comfortable postures.

In condition II, posture comfort and amount of rotation were systematically varied. We specifically looked at trials where the hexagon had to be grasped with the preferred grasping pattern and subsequently rotated. The rationale was that these trials best reflect the natural behavior of individuals with HCP, as they are known to rarely engage a grasping pattern that does not optimize start-posture comfort (Mutsaarts et al., submitted; Steenbergen, Hulstijn, & Dortmans, 2000). We were particularly interested in the effect of the complexity of the latter movement part on anticipatory planning, as reflected in the different movement parameters. Based on the alleged incomplete planning in individuals with HCP, our second hypothesis was that the HCP participants would not anticipate the amount of rotation before movement.
onset (as reflected in the initial reaction time) given a preferred (optimal) start-posture. Rather, these anticipation effects were expected to occur in later phases of the movement sequence. Hence, we predicted longer initial reaction times for the larger rotations only for the control group. In contrast, for the HCP participants, we predicted longer movement times and/or longer second reaction times for the larger rotations.

Finally, we also examined the effect of the number of movement parts in a movement sequence on the different movement parameters. Following Klapp (1995, 2003), for the control participants, we expected longer initial reaction times for condition II as compared to condition I, as the former consisted of more movement parts (i.e., grasping and rotating versus grasping). Such an effect was not predicted for the HCP participants. However, due to the specific set-up of the experiment (different starting cues in both conditions), the results of a comparison of initial reaction times for both conditions is indirect and consequently difficult to interpret. Therefore, we also compared the movement times for both conditions. The rationale for this comparison was that if HCP participants continue planning after movement onset, that is, if they indeed use a ‘step-by-step’ planning process, we expected that the effect of sequence length (i.e., Condition II minus Condition I) would also be reflected in the movement times, with longer movement times for longer sequences (Condition II). This should not be the case for the control group, since they would have finalized their planning processes prior to movement onset.

In sum, in this study, anticipatory planning in individuals with HCP was examined in detail for a complex object manipulation task, by capitalizing on both the complexity and the number of elements in the movement sequences. The overall goal of the study was to gain more insight into the nature of the planning disorder in HCP.

**Method**

**Participants**

Seven adolescents with right spastic hemiparesis (viz., left hemispheric damage; mean age 17.3 years, SD 2.1 years) and 7 neurologically healthy control participants (all left-handed, mean age 19.3 years, SD 1.4 years) participated in the experiment on a voluntary basis. We selected only HCP participants with left hemispheric damage, because it has been shown that problems in planning are most profound in this subgroup (e.g., Steenbergen et al., 2004). In order to maximize the match between the HCP participants and the controls, we
used left-handed controls. Participants with hemiparesis used their left (ipsilesional) hand. At the moment of testing, the hemiparetic participants were students from the Werkenrode Institute (Groesbeek, The Netherlands) where they followed an adapted educational program. They were selected based on being diagnosed as having spastic hemiparesis due to cerebral palsy (HCP). Because of the fact that they were students of a school, instead of patients in a medical clinic, only limited information on individual neuropathology was available. To characterize the participants in terms of gross hand function of the type studied here, we administered the Box and Block test (Mathiowetz, Volland, Kashman, & Weber, 1985) according to the instructions in the test-protocols (See also Table 1). The test-retest reliability at six-month intervals of the Box and Block test has been reported as rho coefficients of .937 and .976 for the left and right hand, respectively (Mathiowetz et al.). Additional information on the HCP participants is given in Table 1. The control participants were psychology students from the Radboud University.

All participants signed an informed consent. 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.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Age</th>
<th>Pref. hand</th>
<th>Non-pref. Hand</th>
<th>Diagnosis</th>
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<td>26</td>
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<tr>
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<td>F</td>
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<td>29</td>
<td>12</td>
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<td></td>
<td>5F/2M</td>
<td>19.3</td>
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Note. HCP Hemiparetic Cerebral Palsy. *number of blocks transported in 60 seconds.

Experimental set-up and apparatus

The participants were comfortably seated on an ergonomic chair positioned in front of a table at the level of the abdomen. On this table, a custom made apparatus was placed. It consisted of a metal platform (measuring 32 cm in length and 24 cm in width), with a wooden disk (measuring 40 cm in diameter) attached on top (see Figure 1a). The disk could be tilted at a slope between 0° and 90° relative to the platform. A plastic hexagonal knob (diameter, 11
cm and depth 6 cm) was attached to the center of the disk. The hexagon could freely rotate around its vertical axis with only limited friction. Rotation was registered with a sampling frequency of 1000 Hz. At the front and at the sides of the hexagon, a metal touch sensor was placed, which recorded

![Image of grasping patterns]

_Figure 1a._ The five possible grasping patterns. The numbers 1 to 5 indicate grasping pattern 1 to 5. _b._ Schematic drawing of the custom made apparatus. At the edge of the disk, 6 Light Emitting Diodes (LEDs) are placed, numbered 1 to 6. _c._ Schematic drawing of the start box. Participants placed their left fist at the dark gray circle at the bottom of the rectangular box.

the moment that the hand touched the hexagon (precision 1 ms). At 0.5 cm from the edge of the disk six LEDs (Light Emitting Diodes) were placed, at positions 1:6 (see Figure 1b). Furthermore, at each of the six sides of the hexagon a red arrow was inserted. A start box (see Figure 1c) was used for reaction time measurements (precision 1 ms).

**Design and procedure**

The experiment consisted of two main conditions (Ia and IIa) and two control conditions (Ib and IIb). As a starting posture in all conditions, participants placed their left (dominant) fist (little finger below) in front of them on the start box. Next, all six LEDs lighted up for a period of 1000 ms (priming cue). This cue warned the participant for the subsequent starting cue that indicated the beginning of a trial.
As a starting cue in main condition Ia and control condition Ib, one of five LEDs (1:5, see Figure 1b) lighted up for 50 ms after a random delay of 600 to 1500 ms following the priming cue (see Figure 2a). In the main condition (Ia), participants were instructed to grasp the hexagon as quickly as possible following the starting cue, using the grasping pattern that corresponded with the position of the starting cue (see Figure 1a and 1b). For example, if LED 1 was the starting cue, the task was to grasp the hexagon using grasping pattern 1. In the control condition (Ib), participants were instructed to touch the front of the hexagon with the index finger as quickly as possible after the starting cue appeared. This control condition was performed to ensure that the results of main condition Ia could not be ascribed to differences pertaining to the speed of perceptual processes associated with the different locations of the LEDs.

The starting cue in both main condition IIa and control condition IIb consisted of two LEDs (LED1 and LED2) that were lighted up sequentially following a random delay ranging from 600 ms to 1500 ms after the priming cue. Each LED was lighted up for 50 ms with a 50 ms interval demarcating the two (see Figure 2b). LED2 was either 60° or 120° away from LED1 (see Figure 1b). In the main condition (IIa), participants were instructed to grasp the hexagon as quickly as possible after the starting cue, using the grasping pattern that corresponded with LED1. Next, they had to rotate the hexagon to the position that corresponded with LED2. For example, if the position of LED1 was 3 and the position of LED2 was 4, the task was to grasp the hexagon using grasping pattern 3 and subsequently rotate it to LED position 4. In the control condition (IIb), participants were instructed to touch the front of the hexagon as quickly as possible after the starting cue. This control condition was performed to ensure that the results of main condition IIa could not be ascribed to differences pertaining to the speed of perceptual processes associated with different locations of the two successive LEDs.

Main condition Ia consisted of 50 trials, determined by 5 LEDs * 10 replications. Control condition Ib consisted of 25 trials, determined by 5 LEDs * 5 replications. Main condition IIa consisted of 140 trials, determined by 14 combinations of LED1 and LED2 * 10 replications. Control condition IIb consisted of 28 trials, determined by 14 combinations of LED1 and LED2 * 2 replications. Within each condition, all trials were randomized. The order in which the participants performed the different conditions was randomized.

During the practice sessions that took place prior to the start of the experiment, adjustments to the apparatus were made by the experimentator. It consisted of adjusting the
slope of the disk and the distance from the apparatus to the front edge of the table to each participant’s active range of motion. This resulted in slopes ranging from 60° to 80° and distances ranging from 9 to 22 cm. These adjustments were made to ensure that for each individual participant the same 5 distinct grasping patterns were possible, with the fingers at position 1, 2, 3, 4, or 5, respectively (see Figure 1a). The participants used the practice sessions to familiarize themselves with the different grasping patterns, as well as to find a comfortable sitting posture that they were asked to maintain during the experiment. On average, practice sessions took about 10 minutes, including adjustments and instructions.

![Diagram](image)

**Figure 2a.** Event structure for main condition la and control condition lb. The priming cue (1000 ms), a random interval (600-1500 ms), and the starting cue (50 ms) are schematically represented. **b.** Event structure for main condition lla and control condition llb. The priming cue (1000 ms), a random interval (600-1500 ms), and the priming cue, consisting of LED1 (50 ms), an interval (50 ms), and LED2 (50 ms) are schematically represented.
Data analyses

The data were analyzed off-line. Three movement parameters were determined. Initial Reaction Time (RT1) was defined as the interval between the starting cue and the moment the hand released the start box. Movement Time (MT) was defined as the interval between the moment the hand released the start box and the moment the hand first made contact with the hexagon, as registered by the touch sensor. Finally, in main condition IIa a Second Reaction Time (RT2) was measured. It was defined as the interval between the moment the hand first touched the hexagon and the moment the hexagon was rotated 1 degree, viz., start of the rotation movement.

Statistical analyses

We analyzed the means of the dependent variables across the replications of each condition and across the conditions using repeated measures analysis of variance (ANOVA). The design consisted of one between-subject factor, Group (controls versus HCP), and three within-subject factors, LED Position (1:5), Amount of Rotation (60° versus 120°), and Sequence Length (Condition Ia versus Condition IIa). When relevant, post-hoc tests were performed by means of exhaustive pairwise comparisons. An alpha level of .05 was used for all statistical tests, but Bonferroni corrections were applied to the post-hoc tests.

Results

General task performance

Both the HCP participants and the control participants were able to successfully perform the task. Due to the intensive nature of the experiment, the HCP participants needed substantially more resting breaks than the control participants to properly finish the experiment. We classified approximately 4% of the trials as invalid because of extremely long reaction times and/or movement times (a deviation from the mean of more than three times the within-subject standard deviation was used as an outlier-procedure). The invalid trials were excluded from data analyses.

Condition I: effect of posture comfort on RT1

Figure 3a represents the mean initial reaction times (RT1) for both groups for each of the five LED positions (i.e., grasping pattern 1:5) in main condition Ia. The statistical analysis showed no significant Group*LED Position interaction.
Figure 3a. Mean initial reaction times (RT1) for the control group (squares) and the HCP group (diamonds) for each of the five LED positions in main condition Ia. Error bars represent between-subjects variability (SDs). b. Mean movement times (MT) for the control group (squares) and the HCP group (diamonds) for each of the five LED positions in main condition Ia. Error bars represent between-subjects variability (SDs).
(F(4,9)=1.12, p=ns, $\eta^2=.33$), which suggests that the RT1 patterns are similar for both groups. A main effect of LED Position was established (F(4,9)=6.35, $p=.001$, $\eta^2=.74$). Post-hoc analysis showed that RT1 was significantly shorter for LED position 3 than for LED positions 1 and 5 ($p=.009$ and $p=.02$, respectively). Also, RT1 was longer for LED position 1 than for LED position 2 ($p=.008$). In Table 2, RT1s are presented of the five different LED positions for the individual participants as well as of the overall scores for the groups.

With respect to the between-subjects effects, in Figure 3a it can be observed that the control group reacted faster than the HCP participants. Indeed, the analysis showed a significant main Group effect (F(1,12)=9.84, $p=.009$, $\eta^2=.45$).

The participants also performed a control condition (lb), in which they had to touch the front of the hexagon with the index finger, instead of grasping it. For this control condition, no main effect of LED Position (F<1) was found. Therefore, we conclude that the effects of LED position on RT1 found in main condition la were not confounded by processes associated with the speed of perception of the LEDs at the different positions.

Besides RT1, we also plotted mean MT for the five LED positions in Figure 3b. This was done to test whether the movement trajectories towards the different grasping patterns coincided with the RT1 patterns observed in Figure 3a, that is, longer and more complex movement trajectories for the less comfortable grasping patterns. The statistical analysis showed that the MT patterns are similar for both groups, since no significant Group*LED Position interaction (F<1) was established. In addition, as was also shown for RT1, there existed a main effect of LED Position for MT (F(4,9)=7.06, $p=.007$, $\eta^2=.76$). Post-hoc analysis showed that MT was significantly shorter for LED position 3 than for LED positions 4 and 5 ($p=.006$ and $p=.002$, respectively). A statistical trend in the same direction was shown for LED position 3 as compared to LED position 1 (p=.056). Also, MT at LED position 4 was significantly shorter than at LED position 5 (p=.04).

With respect to the between-subjects effects, in Figure 3b it can be observed that the control group moved faster that the HCP participants. The analysis showed a statistical trend in this direction (F(1,12)=4.47, $p=.056$, $\eta^2=.27$), thereby only partly corroborating this observation.
Table 2

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<td>403(35)</td>
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</table>

**Condition II: effect of Amount of Rotation on RT1, MT, and RT2**

Figure 4 shows mean initial reaction times (RT1), mean movement times (MT), and mean second reaction times (RT2) of the control group (left panel) and the HCP group (right panel) in main condition IIa. The data depicted in Figure 4 are from trials in which participants grasped the hexagon using the preferred grasping pattern 3 (i.e., LED1 = 3). The light gray bars represent the trials in which participants subsequently rotated the hexagon 60° clockwise or counterclockwise (i.e., LED2 = 2 or 4). The dark gray bars represent the trials in which participants subsequently rotated the hexagon 120° clockwise or counterclockwise (i.e., LED2 = 1 or 5).

No significant Group*Amount of Rotation interaction was found as regards RT1 (F(1,12)=1.14, p=ns, $\eta^2=.09$). For the entire data set, the statistical analysis revealed a main effect of Amount of Rotation (F(1,12)=9.27, p=.01, $\eta^2=.44$), which indicates that RT1 was significantly longer for the larger rotation than for the smaller rotation. With respect to MT, there was a significant Group*Amount of Rotation interaction (F(1,12)=7.24, p=.02, $\eta^2=.38$). Step-down analyses of this interaction revealed that for the HCP group MT was shorter for the smaller rotation than for the larger rotation (F(1,6)=1.14, p=.02, $\eta^2=.63$), whereas this was not the case for the control group (F<1). In addition, a significant Group*Amount of Rotation interaction was established for RT2 (F(1,12)=6.69, p=.024, $\eta^2=.36$). Comparable to MT, step-down analyses of this interaction showed that for the HCP group RT2 was shorter for the
smaller rotation than for the larger rotation \(F(1,6)=6.31, \ p=.04, \ \eta^2=.51\), whereas for the controls no such effect was found \(F<1\).

With respect to the between-subjects effects of RT1, MT, and RT2, it was shown that both MT and RT2 were significantly longer for the HCP group than for the control group \((F(1,12)=17, \ p=.001, \ \eta^2=.59\) and \(F(1,12)=6.41, \ p=.026, \ \eta^2=.35\), respectively). RT1 showed a statistical trend in the same direction \((F(1,12)=3.84, \ p=.074, \ \eta^2=.24\).

The participants also performed a control condition (IIb), in which they had to touch the front of the hexagon with the index finger, instead of grasping and rotating it. The statistical analysis revealed no significant main effect of Amount of Rotation for RT1 and MT \((F(1,12)=1.15, \ p=ns, \ \eta^2=.09\) and \(F<1\), respectively). Hence, we conclude that the effects found in main condition IIa are not confounded by processes associated with the speed of perception of the position of the two successive LEDs.

\[\begin{array}{c}
\text{Figure 4. Initial reaction times (RT1), movement times (MT), and second reaction times (RT2) for the control group (left panel) and the HCP group (right panel) in main condition IIa, for all trials in which LED1 was 3. The light gray bars represent the trials in which LED2 was 2 or 4, and the dark gray bars represent the trials in which LED2 was 1 or 5. Error bars represent between-subjects variability (SDs).}
\end{array}\]

**Condition I and II: comparison of MT**

To examine the effect of Sequence Length, we compared mean RT1 in main condition Ia and main condition IIa. This was done with respect to the preferred grasping pattern (i.e., LED1=3), as established in main condition Ia. No significant Group*Sequence Length
interaction was found (F<1). In addition, no main effect of Sequence Length with respect to RT1 was established, although there was a statistical trend (F(1,12)=3.3, p=.09, $\eta^2 = .22$), which suggests that RT1 was longer for main condition IIa as compared to main condition Ia. Still, it must be noted that the different starting cues in both conditions (one LED in condition I versus two successive LEDs in condition II) cause these results to be somewhat difficult to interpret.

We also examined the effect of Sequence Length on MT. The Group*Sequence Length interaction just failed to reach statistical significance (F(1,12)=4.24, p=.062, $\eta^2 = .26$). Step-down analysis revealed that for the control group there existed no main effect of Sequence Length (F<1), whereas for the HCP participants, MT tended to be longer for main condition IIa as compared to main condition Ia, as shown by a statistical trend (F(1,6)=5.29, p=.061, $\eta^2 = .47$).

In Figure 5, MT is presented for main condition Ia and for main condition IIa. For the latter condition, both the 60° rotation trials and the 120° rotation trials are plotted. In this way, the effect of both Sequence Length (statistical trend for the HCP group) and Amount of Rotation (significant difference for the HCP group) are depicted in one graph. Note that for the effect of Sequence Length, the average MT of main condition IIa (both 60° and 120°) is compared with MT in main condition Ia.

![Figure 5](image-url)

*Figure 5. Mean movement time (MT) for LED position 3 in main condition I, 60° rotation in condition II and 120° rotation in condition II for the HCP group and the control group. Error bars represent between-subjects variability (SDs).*
Discussion

Summary main results

In the first condition of the present study, participants had to grasp a hexagonal knob using one of five possible grasping patterns, which varied systematically in terms of posture comfort. We predicted shorter initial reaction times for the more comfortable grasping patterns. The results showed an initial reaction time advantage for the most comfortable posture (grasping pattern 3) as compared with the least comfortable postures (grasping patterns 1 and 5) for all participants, which confirmed our hypothesis. The finding that the movement time patterns closely resembled the initial reaction time patterns suggests that for grasping the less comfortable grasping patterns longer and more complex movement trajectories were indeed required.

In the second condition, participants had to grasp the hexagon and subsequently rotate it either 60° or 120° in a clockwise or counterclockwise direction. We compared the different movement parameters as a function of the required amount of rotation. The results showed that initial reaction times were longer for the larger rotations. More important, for the HCP participants, an effect of amount of rotation was established during latter phases of the movement sequence, with longer movement times and longer second reaction times being associated with larger rotations. In contrast, for the controls no such effects were found.

Finally, we compared the initial reaction times and movement times between both conditions (viz., grasping versus grasping and rotating) to examine possible effects of sequence length. No effects were found, although a statistical trend was established for the HCP participants with respect to movement times, which indicates that movement times tended to be longer for the longer sequences (Condition II).

Possible confounding factors

Two factors may to some degree complicate the interpretation of the present findings. First, we established that on almost all measures the HCP participants were slower than the controls. This finding substantiates the claim that the ipsilesional side of HCP has subtle motor deviations as well (Steenbergen et al., 2004). Since this general slowing was a common observation, and, more important, because it was a very systematic finding in the present study, we are confident that it does not impede our interpretation of the main results obtained. The second possible confounding factor regarded the speed of perception of the different
LEDs that served as starting cues. To control for this, the participants were instructed to make
the same movements (touching the front side of the hexagon) irrespective of the position of
the LED (first control condition) or LEDs (second control condition) that switched on.
Because we did not find systematic variations in initial reaction time and movement time as a
function of the position of the LED(s), the results of the main conditions can not be attributed
to differences in the speed of the processes that are associated with perception of the different
LED locations. Therefore, we are confident that these processes do not confound the
interpretation of the results.

Major implications for anticipatory planning in HCP individuals

The main goal of the present study was to lay bare the deviant anticipatory planning
processes in individuals with HCP. We were able to make inferences thereon, by
manipulating both the complexity and the number of elements in the tasks that had to be
performed under speeded task constraints (for comparable reasoning and analyses in healthy
subjects, see Fleming, Klatzky, & Behrmann, 2002). From the main findings summarized
above, two major conclusions can be drawn.

First, we discuss the issue whether HCP participants have the general ability to
internally represent an upcoming task. Evidence in favor of this capability was already found
for individuals with congenital hemiparesis (Gorden, Charles, & Duff, 1999; Gordon & Duff,
1999; Mutsaarts et al., submitted; Steenbergen et al., 2004). Furthermore, it has been shown
that the ability to internally represent motor actions is intact in individuals with hemiparesis as
a result of stroke, both for acute (Johnson, 2000) and chronic patients (Johnson, Sprehn, &
Saykin, 2002; but see Takahashi & Reinkensmeyer, 2003). In the present study, especially the
striking resemblance between the effect of posture comfort on the initial reaction time
measure for both the controls and the HCP participants in the first condition adds additional
weight to the conclusion that individuals with HCP have retained the ability to internally
represent motor actions, in this case the different grasping patterns.

Second, given the fact that the sensitivity for task complexity (with respect to amount
of rotation) of the HCP participants emerged during latter phases of the movement sequences,
we conclude that they have not completed the planning processes of the entire movement
sequence before movement onset. Instead, they seem to segment the movement sequence into
its constituent parts (grasping and rotating). Consequently, these movement parts are
processed and executed sequentially, as opposed to the parallel incorporation of the entire movement sequence into an integrated motor plan.

**A broader perspective on action planning in HCP**

In itself, the aforementioned segmentation is not remarkable, since a number of studies have shown similar effects in healthy individuals (e.g., Fleming et al., 2002; Haggard, 1998), especially when movement sequences become longer and more complex. In the present study however, the controls appeared to have completed planning before movement onset, whereas the HCP participants showed effects of task complexity even after completing the first grasping phase, that is, just prior to the rotation of the hexagon. In two studies on anticipatory control of object manipulation, Eliasson et al. (1991, 1992) established comparable findings regarding the coordination of grip and lift forces in individuals with HCP (see also, Gordon & Duff, 1999; Steenbergen & Kamp van der, 2004). In the studies of Eliasson et al., HCP participants were asked to grasp a squared object and subsequently lift it. In such a task, healthy subjects generated positive grip and lift forces in parallel resulting in a smooth lift of the object. In contrast, HCP individuals first applied (excessive) grip force to the object followed by a negative (downward) lift force, resulting in extended durations in contact with the object before it was lifted (see also Steenbergen, Hulstijn, Lemmens, & Meulenbroek, 1998). A similar sequential decrease in grip and load force in HCP during the release of an object was found by Eliasson and Gordon (2000, see also Gordon, Lewis, Eliasson, & Duff, 2003). Sequentiation was also shown during bimanual coordination (Hung, Charles, & Gordon, 2004). In a ‘drawer opening’ task individuals with HCP showed a reduced overlap between the movements of both hands. That is, the two movement objectives (i.e., opening a drawer and pushing a button) were completed sequentially, rather than simultaneously as was shown for controls. In sum, the established segmentation of movement sequences into its constituent parts appears to reflect a more general characteristic of the deviant anticipatory planning in individuals with HCP.

**Application to recent models on sensory-motor action**

A possible explanation for the observed deviation in anticipatory planning in individuals with HCP that has been previously suggested (Gordon & Duff, 1999; Steenbergen et al., 2004) may be sought in the concept of internal models (Wolpert & Ghahramani, 2000).
In this concept, it is proposed that the nervous system uses sensory motor mappings to anticipate and adapt to dynamic environments (e.g., Shadmehr & Mussa-Ivaldi, 1994). In a forward internal model, the sensory consequences of motor commands are predicted, whereas the motor commands required to achieve a desired outcome are specified in an inverse internal model (e.g., Blakemore, Wolpert, & Frith, 2002). As the HCP participants in the present study showed similar performance characteristics (viz., systematic variation of reaction time as a function of comfort of the grasping pattern) as the controls in the first condition, we speculate that the internal model responsible for anticipatory grip planning may not be impaired for simple prehension movements. This speculation is corroborated by the results of Gordon and Duff (1999). They tested the ability of HCP children to form and use an internal model that predicts the forces necessary for picking up objects. Specifically, they examined whether this anticipatory planning can be generalized across hands. The results showed that sensory information from the non-affected hand can be used for anticipatory scaling of isometric force increase during subsequent lifts with the contralateral affected hand. These findings suggest that the initial lack of anticipatory control usually observed in the involved hand in children with HCP is likely to be based on disturbed sensory input.

The results of the second condition of the present study showed that HCP participants did not plan the entire movement sequence prior to movement onset. In the context of internal models, this finding may imply a capacity problem to form and/or utilize an internal model for grip planning of complex movement sequences. On the one hand it might reflect a limitation in the capacity of the forward model to properly predict the sensory consequences of the necessary motor command on subsequent parts of the movement sequence (i.e., rotating the hexagon). Alternatively, it could also reflect an insufficient capacity of the inverse model to specify the motor commands required to achieve the entire movement sequence. Given the set-up and design of the present study, we are not able to falsify either of these possibilities.

Another recent model of goal-directed action that is relevant in the context of the present study is the planning-control model that was proposed by Glover (2004). This model posits separate visual representations subserving planning and on-line control of movements. Whereas planning is presumed to be affected by task context and semantics, on-line control is thought to be primarily influenced by the spatial constraints of the target. When applied to the present study, task context (amount of rotation) should affect the planning of the action, whereas on-line control should be affected by the dimensions of the hexagon, which were kept constant throughout the experiment. Based on this model, the manipulations in our study should predominantly affect the planning and to a less amount the on-line control of the
movements. Indeed, we established effects of amount of rotation on initial reaction time. This suggests that task context had an effect on movement planning (under the assumption that planning is reflected in reaction time measures). For the controls, no effect of amount of rotation was found on movement time (and second reaction time), indicating that task context did not have an effect on on-line control (under the assumption that on-line control is reflected by movement time) for these participants. In contrast, for the HCP participants, both movement time and second reaction time were affected by the amount of rotation in the grasp and rotation task. As argued before, these results indicate that planning in these participants is not complete before movement onset, but may continue during execution of the movement (movement time). At the same time, they point to segmentation of the planning processes for the entire movement sequence into its constituent parts (first grasping, second rotating), as evidenced by the effects of amount of rotation on second reaction time. These findings suggest that the planning-control model may be extended to explain the pattern of results of this clinical population by proposing multiple planning-control phases during the movement sequence. However, as we only measured movement time, and not the kinematic features during execution of the movement, it could not be verified to what extent planning proceeds during execution. As an example of this, Glover and Dixon (2002) showed that errors in movement planning were corrected during on-line control. When subjects had to grasp objects with similar dimensions on which either ‘LARGE’ or ‘SMALL’ was printed, peak grip aperture was initially affected by the words (planning error), but this effect gradually disappeared as the hand approached the object (on-line correction). In order to test the applicability of the planning-control model for movement planning in HCP participants, a more detailed analysis of the execution phase is needed. In particular, changes in hand orientation during the early part of execution should be examined, as these are indicative of both grip planning and corrective control processes during complex object manipulation (Steenbergen & Kamp van der, 2004; Mutsaarts et al., 2004). Still, the effect of task complexity (amount of rotation) on movement time that we found for HCP participants may suggest that planning processes continue during execution.
Chapter 5

Impaired motor imagery in right Hemiparetic Cerebral Palsy
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 behavior. 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.

Based on:
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, Thiel van, Hulstijn, & Meulenbroek, 2000), more variable hand trajectories (Thiel van, Meulenbroek, Smeets, & Hulstijn, 2002), and increased trunk involvement (Roon van, 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 unaffected 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, Heugten van, & 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 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, & Umiltà,
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., Crammond, 1997; Jeannerod, 1994, 1995, 2001; Johnson, 1998; 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 (Decety et al., 1994; Kosslyn et al., 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 assess 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 behavior (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, DiGirolamo, Thompson, and Alpert (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.

Method

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, SD = 2.0 years) participated in the study, after signing a written informed consent form. They received 5 euros 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, SD = 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.

Table 1
Participant Information (Standard Deviations in Parentheses). The IQ Scores are from the Wechsler Intelligence Scale for Children – Revised (WISC-R)

<table>
<thead>
<tr>
<th>HCP</th>
<th>Participant</th>
<th>Gender</th>
<th>Age</th>
<th>Cause</th>
<th>Total IQ</th>
<th>Performance IQ</th>
<th>Verbal IQ</th>
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<td></td>
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<td>79</td>
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<td>81</td>
<td>-</td>
</tr>
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Mean Left

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<td>(16)</td>
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Left

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<th>Gender</th>
<th>Age</th>
<th>Cause</th>
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<th>Performance IQ</th>
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<td></td>
<td></td>
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<td>101</td>
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<td>-</td>
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Right

<table>
<thead>
<tr>
<th>HCP</th>
<th>Participant</th>
<th>Gender</th>
<th>Age</th>
<th>Cause</th>
<th>Total IQ</th>
<th>Performance IQ</th>
<th>Verbal IQ</th>
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<td>61</td>
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<td>94</td>
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<td>SW</td>
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<td>Cerebral Palsy</td>
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<td>75</td>
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Mean Right

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<thead>
<tr>
<th>Mean</th>
<th>15.9</th>
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<th>73</th>
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<tr>
<td></td>
<td>(2.4)</td>
<td>(13)</td>
<td>(19)</td>
<td>(13)</td>
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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).

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 Figure 1). All stimuli measured approximately 8 cm in diameter when displayed on a monitor.

![Figure 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.](image)

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 by 17 mm) placed at the centre of the apparatus, was used to record responses with an accuracy of 1 ms. Also, a 17 inch monitor was used to display the stimuli.

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/affected 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 sagittal plane. In a similar vein, for the participants who responded with the left hand...
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.

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 Figure 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 seconds. Subsequently, a
fixation cross appeared in the center of the screen for a random period (between 0.8 and 1.3
seconds), 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.

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 Spearman rank-order correlations to statistically analyze the correlations between IQ-scores and number of incorrect responses across all HCP participants.

Results

Reaction time
Figure 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 ($F(1)=3.154, p=ns, \eta^2=.24$). Thus, for participants with right HCP there was no linear increase of RT as a function of increased Angle of Rotation.

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).
Figure 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.

Figure 3. Incorrect responses (as a percentage of total trials). Error bars represent between-subjects variability (SDs).
Next, we calculated the incorrect responses (as a percentage of total trials) for each group separately (see Figure 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, $\chi^2(2)=4.374, p=ns$.

Finally, in Figure 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 ($z=1.067, p=ns$).

![Figure 4](image_url)

**Figure 4.** Incorrect responses (as a percentage of total trials). Error bars represent between-subjects variability (SDs). The * indicates that participants with left HCP made significantly more errors for the left hand stimuli than for the right hand stimuli.

**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.

<table>
<thead>
<tr>
<th></th>
<th>Number of errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal IQ</td>
<td>-.009 (.967)</td>
</tr>
<tr>
<td>Performance IQ</td>
<td>-.44 (.101)</td>
</tr>
<tr>
<td>Total IQ</td>
<td>-.551 (.052)</td>
</tr>
</tbody>
</table>

**Table 2**

Spearman 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

**Discussion**

**Main results**

Based on the idea that Motor Imagery (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 behavior. 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 Figure 3), as well as the lack of linear increase in reaction times as a function of angle of rotation (see Figure 2), since no verification of the initial ‘educated guess’ takes place.

**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 et al. (2000, 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 et al., 2000, 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.

**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 Figure 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.

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.
Epilogue
The central concept of this thesis is: *Anticipatory motor planning*. At first sight this concept might appear pleonastic, because planning already presupposes some degree of anticipation. However, by adding *anticipatory* to the concept of motor planning, it is emphasized that this type of planning involves taking into account future task goals or demands. In the first three experiments that are described in this thesis, we examined in detail the anticipatory motor planning ability of individuals with Hemiparetic Cerebral Palsy (HCP). To do so, we exploited a well-known phenomenon denoted *end-state comfort effect* (Elsinger & Rosenbaum, 2003; Rosenbaum, Engelbrecht, Bushe, Loukopolous, 1993; Rosenbaum & Jorgenson, 1992; Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993; Short & Caraugh, 1997, 1999). The end-state comfort effect is the tendency of people to sacrifice comfort at the beginning of a movement sequence in order to achieve optimal comfort at the end. By showing such an end-state comfort effect, individuals are supposed to have been engaged in anticipatory motor planning. The findings of the first three studies of this thesis indicate that the ability for anticipatory motor planning is reduced in individuals with HCP. We observed that they used several alternative movement planning strategies. However, these strategies, which were not based on obtaining end-posture comfort, did not always enable them to successfully perform the experimental task. In the first study, the participants with HCP *re-used previously selected grips* when planning their current grip. Next, two different alternative strategies were suggested by the findings of the second study. Participants selected an *optimal initial grip* and they *used immediately available visual information* to select a grip. Finally, the analyses of the different time aspects in the third study revealed a *step-by-step planning strategy*, when the task consisted of more than one movement part. In the fourth and final experimental study described in this thesis, we examined the hypothesis that impaired motor imagery underlies the anticipatory motor planning deficit in individuals with HCP. An important finding of this experiment is that for the participants with right HCP (left brain damage) motor imagery was indeed compromised. In contrast, the participants with left HCP (right brain damage) displayed motor imagery abilities comparable to the neurologically healthy control participants. Below, a brief synopsis of the four experimental studies is provided.

The study presented in chapter 2 provides a detailed analysis of the prehension movements of three adolescents with HCP and a neurologically healthy control group. Participants were instructed to repeatedly grasp a square object of which the position was gradually changed leftwards or rightwards. In half the trials the goal of the task was to lift the object, in the other half it had to be rotated back-and-forth. The results showed that the
participants with HCP based the choice of grip primarily on the previously chosen grip, instead of anticipating the task constraints that were manipulated (object position and task goal). This was in contrast to the control participants, who took into account these task constraints when first taking hold of the object, hence, used anticipatory motor planning.

The study presented in chapter 3 consisted of two separate parts. In the first part, we examined the anticipatory motor planning ability of individuals with HCP into more detail. To do so, we had participants grasp a hexagon and subsequently rotate it a certain degree. The findings confirmed our hypothesis that individuals with HCP have a reduced ability to use anticipatory motor planning. The participants with HCP showed a strong tendency to grasp the hexagon in such a way that initial comfort was ensured. However, this strategy hindered them to successfully perform the task in some conditions. In these conditions, the task was (biomechanically) impossible to be properly carried out as a consequence of the chosen initial grip, and task failures occurred. In contrast, by sacrificing initial grip comfort the neurologically healthy control participants were shown to anticipate posture comfort at the end of the task, i.e., after having rotated the hexagon. In the second part, we manipulated the task context by adding visual information (an arrow), with no further relevance to the task that participants had to perform. Participants with HCP showed to be highly sensitive to this immediately available visual information, as they frequently based the choice of grip on this information. In contrast, control participants were less sensitive for this information, and choose their initial grip such that they ended the task with a comfortable posture. In sum, the findings of both parts of this study indicate that individuals with HCP have anticipatory motor planning deficits, which may be due to their too strict reliance on direct available visual information.

In the study presented in chapter 4, we set out to examine the timing aspects of anticipatory motor planning. The same, but slightly modified, experimental set-up as described in chapter 3 was used. Three modifications were made. First a start button was added for reaction time registration. Second, the hexagon was made touch sensitive to enable registration of the moment of contact with the hexagon. Finally, the hexagon was made rotation sensitive such that the start of the rotation phase could be registered. By measuring these three timing aspects, we were able to examine the timing aspects of the planning processes in the course of performing a sequential object manipulation task. The task was to grasp the hexagon upon a visual starting cue and subsequently rotate it either 60° or 120° clockwise or counterclockwise. The findings suggest that participants with HCP did not to complete their planning processes before movement onset, as reaction times were not
different among the 60° and 120° rotation conditions. This was contrary to the control participants, who showed longer reaction times in the 120° rotations as compared to the 60° rotations. Summing up, the results indicate that participants with HCP planned the latter parts of the action as the movement unfolds, thereby suggesting a step-by-step motor planning strategy.

According to the Prospective Action Model (PAM; Johnson, 2000; Johnson, Rotte, Grafton, Hinrichs, Gazzaniga, & Heinze, 2002), also denoted the imagery as planning theory, anticipatory motor planning of a grip pattern consists of mentally transforming a somatomotor representation of the effector system in order to select a proper response (cf. Parsons, 2003). The mental transformation of somatomotor representations refers to motor imagery. In the study presented in chapter 5 of the present thesis the hypothesis was tested that the anticipatory motor planning deficit of individuals with HCP is caused by impairments in using motor imagery. It is generally assumed that motor imagery mainly involves the left hemisphere. Therefore, in contrast to the first three studies, in which mainly participants with right HCP (left brain damage) took part, in this study both participants with right HCP and left HCP participated. They were instructed to perform a motor imagery task. The results indicated impairments in motor imagery for participants with right HCP, but not for participants with left HCP. Hence, it appears that the ability to mentally simulate complex actions is reduced in individuals with congenital left hemisphere damage.

In closing, the experimental studies described in this thesis contributed to the understanding of anticipatory motor planning in individuals with HCP. By studying different anticipatory motor planning aspects, we have shown that individuals with HCP have a reduced anticipatory motor planning ability. This knowledge may shed a new light on some aspects of the deviant motor behavior of individuals with HCP, which may be used in rehabilitation practice. By laying bare motor imagery impairments in individuals with right HCP (left brain damage), we have uncovered a neural process that may be responsible for the anticipatory motor planning deficit.
References
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Samenvatting
Samenvatting

Op de vraag wat de belangrijkste menselijke vaardigheid is, zal niet vaak het antwoord ‘het grijpen van objecten’ komen. Echter, als de omstandigheden grijpen moeilijker maken dan normaal (bijvoorbeeld door een gekneusde duim) wordt plotseling duidelijk hoe fundamenteel en complex deze vaardigheid eigenlijk is.

Mensen met Hemiparetische Cerebrale Parese (HCP) hebben een halfzijdige verlamming en/of spasticiteit als gevolg van een hersentrauma rond de geboorte. Voor deze mensen is het grijpen van objecten altijd moeilijk. In dit proefschrift staat het vermogen tot grijpen van mensen met HCP centraal. De term HCP refereert primair aan een aandoening van het neuromotorische systeem. Het is dan ook niet vreemd dat verklaringen voor de problemen die mensen met HCP ondervinden bij het grijpen van objecten worden gezocht in de beperkingen in de uitvoering van deze bewegingen. Echter, een alternatieve verklaring is dat er (ook) beperkingen zijn in de planning van grijpbewegingen. In dit proefschrift ligt de nadruk op mogelijke beperkingen in verscheidene planningsaspecten betrokken bij het grijpen van objecten van mensen met HCP. Met name het proces van het selecteren van optimale grijpbewegingen gegeven bepaalde taakdoelen is uitvoerig bestudeerd.

Het selecteren van een greep voor een bepaald object is niet alleen afhankelijk van de fysieke eigenschappen van dat object, maar ook van wat men met het object wil doen. Stel je een glas voor dat op kop op het aanrecht staat. Wanneer het glas moet worden opgepakt om het in de afwasmachine te stoppen, zal waarschijnlijk een greep worden gekozen met de pink onder en de wijsvinger boven. Wanneer het glas moet worden opgepakt om er water in te schenken, zal eerder een greep worden geselecteerd met de pink boven en de wijsvinger onder. In het laatste geval dient het glas namelijk eerst omgedraaid te worden, alvorens er water in geschenken kan worden. De voorgestelde greepkeuze resulteert na het draaien van het glas in een comfortabele handpositie.

Bovenstaand voorbeeld laat zien dat wanneer een grijpbeweging gepland wordt, er niet alleen rekening moet worden gehouden met de direct beschikbare perceptuele informatie (de locatie, vorm en oriëntatie van het te grijpen object). Ook informatie met betrekking tot de toekomstige taakdoelen beïnvloedt de greepkeuze. In dit proefschrift wordt dit aspect van planning motorische vooruitplanning (Engels: anticipatory motor planning) genoemd.

In een serie van vier experimenten is het vermogen van mensen met HCP tot motorisch vooruitplannen onderzocht. In de eerste drie experimenten (beschreven in hoofdstukken 2 t/m 4) is hiervoor gebruik gemaakt van het zogenaamde ‘end-state comfort effect’. Dit is een tendens van mensen om comfort aan het begin van een beweging op te offeren om zodoende comfortabel te eindigen. De rationale om end-state comfort effecten te
gebruiken, is dat het vermogen tot motorisch vooruitplannen een noodzakelijke voorwaarde hiervoor is. Dat betekent dat wanneer iemand objecten volgens het end-state comfort effect grijpt, deze hiermee laat zien te beschikken over het vermogen tot motorisch vooruitplannen.

Omdat de primaire interesse lag in processen geassocieerd met bewegingsplanning in plaats van bewegingsuitvoering, hebben we ervoor gekozen de deelnemers met HCP hun relatief onaangedane hand te laten gebruiken, met uitzondering van het experiment beschreven in hoofdstuk 2. Op deze manier werd zo veel mogelijk voorkomen dat de neuromotorische beperkingen van de aangedane hand interfererden met de resultaten. Ook konden op deze manier meer deelnemers aan de experimenten meedoen, omdat grijpen met de aangedane hand voor veel mensen met HCP bijna niet mogelijk is.

In het experiment beschreven in hoofdstuk 5, is het vermogen tot motorisch vooruitplannen onderzocht zonder de deelnemers daadwerkelijk bewegingen te laten uitvoeren. Hiervoor is gebruik gemaakt van een zogenaamd motor imagery paradigm, waarin bewegingen alleen moeten worden voorgesteld en niet daadwerkelijk mogen worden uitgevoerd.

In het experiment beschreven in hoofdstuk 2 stond de vraag centraal of mensen met HCP langer blijven hangen in een eenmaal gekozen taakoplossing in opeenvolgende pogingen dan een neurologisch gezonde groep controledeelnemers. Daarnaast werden de effecten van twee verschillende taakdoelen op de greepkeuze geanalyseerd. Omdat er werd aangenomen dat de adaptatieprocessen ten aanzien van de neuromotorische beperkingen verschillen per deelnemer, is ervoor gekozen om de gegevens van de drie deelnemers met HCP apart te analyseren. Deze individuele gegevens werden vervolgens vergeleken met een ‘typische’ controledeelnemer (het gemiddelde gedrag van de 11 controledeelnemers). De deelnemers moesten herhaaldelijk een vierkant object grijpen, waarvan de positie tussen de grijpbewegingen telkens naar links of naar rechts werd verschoven. Voordat het experiment begon, werden de deelnemers geïnstrueerd om telkens te kiezen tussen één van twee mogelijke grepen. Om het effect van taakdoelen op de keuze van de greep te kunnen onderzoeken, moest het object opgetild of heen en weer gedraaid worden. De resultaten lieten zien dat de drie deelnemers met HCP langer bleven hangen in een eenmaal gekozen greepkeuze. Zij pasten hun grijpgedrag echter wel aan hun specifieke neuromotorische beperkingen aan. De deelnemer met de ernstigste symptomen koos één greep en bleef gedurende het hele experiment volharden in deze greep, onafhankelijk van de positie van het object en het taakdoel. De twee minder ernstig aangedane deelnemers met HCP bleven in mindere mate hangen in een eenmaal gekozen greep. De ‘typische’ controledeelnemer liet de
taakdoelen meewegen bij de greepkeuze, wat bij geen van de drie deelnemers met HCP het geval was.

Door middel van de twee experimenten beschreven in hoofdstuk 3 werd het vermogen tot motorisch vooruitplannen in meer detail bestudeerd. In het eerste experiment werd onderzocht of de deelnemers met HCP toekomstige perceptueel-motorische eisen van een doel van een bewegingssequentie kunnen anticiperen. Cruciaal in de opzet van het experiment was dat in sommige condities motorisch vooruitplannen noodzakelijk was om de taak succesvol te kunnen uitvoeren. Een zeshoekige knop moest worden vastgepakt met één van vijf mogelijke grepen. De greepkeuze was vrij. Nadat de knop was gegrepen diende deze 60°, 120° of 180° te worden geroteerd, met de klok mee of tegen de klok in. Als de greepkeuze leidde tot een optimaal comfortabele positie bij het vastgrijpen van de zeshoekige knop, dan kon als gevolg van biomechanische beperkingen van de eindpositie deze niet meer 180° worden gedraaid. Maw. een verkeerde greepkeuze kon leiden tot het mislukken van de taak. Bij de deelnemers met HCP mislukten een groot aantal pogingen, terwijl bij de neurologisch gezonde controledeelnemers alle pogingen succesvol waren. Deze bevinding suggereert een beperking in het vermogen tot motorisch vooruitplannen bij mensen met HCP. Gegeven deze beperking wordt de vraag opgeroepen op wat voor soort informatie mensen met HCP dan wel hun greepselectie baseren? Experiment 2 was ontworpen om een mogelijk antwoord te krijgen op deze vraag door te onderzoeken of mensen met HCP gevoelig zijn voor direct aanwezige visuele contextinformatie bij het selecteren van een greep. Hiervoor werd een pijl geplaatst aan een van de zijdes van de zeshoek. Deze pijl had geen verdere relevantie voor de taak. Voor de controledeelnemers bleek de pijl geen invloed te hebben op de greepkeuze. Voor de deelnemers met HCP daarentegen was de plaats van de pijl van grote invloed op de greepkeuze. Zij grepen namelijk vaker daar waar de pijl geplaatst was, los van het eigenlijke taakdoel. Geconcludeerd werd dan ook dat direct aanwezige visuele contextinformatie gebruikt wordt door mensen met HCP om hun greepkeuze op te baseren.

In het experiment beschreven in hoofdstuk 4 is het vermogen tot motorisch vooruitplannen in een complexe object-manipulatietak onderzocht. Op deze manier werd getracht meer inzicht te krijgen in de tijdsaspecten van het proces van motorisch vooruitplannen bij mensen met HCP. Voor dit experiment was een aantal kleine aanpassingen aangebracht aan de experimentele opstelling zoals die in de experimenten beschreven in hoofdstuk 3 werd gebruikt. Allereerst was er een reactietijdknop toegevoegd, om het exacte moment waarop een deelnemer een beweging startte te kunnen registreren. Daarnaast werd de zeshoek voorzien van een aanraakdetector, zodat kon worden vastgesteld wanneer een
deelnemer de zeshoek vastgreep. Ten slotte werd de zeshoek voorzien van een draaidetector. Op deze manier kon het moment waarop een deelnemer de zeshoek begon te roteren, worden vastgelegd. Door de reactietijd, het aanraakmoment en het draaimoment te meten, kon het effect van verschillende planningsprocessen gedurende een complexe object-manipulatietoefening worden onderzocht. De deelnemers werden geïnstrueerd de zeshoek te grijpen met een van te voren aangegeven greep. De keuze hierin was dus in tegenstelling tot de experimenten beschreven in hoofdstuk 3 niet vrij. In een aparte conditie dienden de deelnemers vervolgens de zeshoek 60° of 120° met de klok mee of tegen de klok in te draaien. Met betrekking tot reactietijd werd voor de deelnemers met HCP geen verschil geconstateerd tussen 60° of 120° draaien. Bij de neurologisch gezonde controdeelnemers daarentegen bestond er wel een verschil in reactietijd. Deze was namelijk langer bij de 120° taak dan bij de 60° taak. Hieruit werd geconcludeerd dat de deelnemers met HCP begonnen met bewegen alvorens de hele bewegingssequentie te hebben gepland. De extra planning die de 120° taak met zich meebracht, vond plaats gaandeweg de grijpbeweging.

In zogenaamde motor imagery taken worden bewegingen van (delen van) het lichaam mentaal voorgesteld, zonder deze daadwerkelijk uit te voeren. Algemeen wordt aangenomen dat motor imagery een kritische factor is in het proces van motorisch vooruitplannen. Op basis hiervan ontstond de hypothese dat de beperkingen in motorisch vooruitplannen bij mensen met HCP worden veroorzaakt door beperkingen in het vermogen tot motor imagery. Meer specifiek werden beperkingen in motor imagery verwacht bij mensen met rechts HCP (linkerhersenschade). Deze specificering is gebaseerd op bevindingen van Steenbergen, Meulenbroek, and Rosenbaum (2004), waarin een verschil in het vermogen tot motorisch vooruitplannen werd vastgesteld tussen mensen met links HCP en mensen met rechts HCP, waarbij mensen met rechts HCP meer beperkingen hadden. Aangezien aan de studies uit hoofdstuk 2, 3 en 4 hoofdzakelijk deelnemers met rechts HCP hebben meegedaan, zijn de resultaten hiervan in lijn met deze bevinding. Om hemisperische verschillen ten aanzien van het vermogen tot motor imagery te onderzoeken, werden in deze studie 19 deelnemers met HCP geselecteerd, waarvan 8 met links HCP en 11 met rechts HCP. Deze deelnemers, inclusief een groep van 9 neurologisch gezonde controdeelnemers kregen twee motor imagery taken voorgeschoteld. Op basis van plaatjes van handen of handen met hamers diende een beoordeling te worden gemaakt of het om een linkerhand of rechterhand ging. De plaatjes van de handen (met of zonder hamer) werden aangeboden in verschillende oriëntaties. De deelnemers met rechts HCP lieten ernstige beperkingen in het vermogen tot motor imagery zien. Zij maakten veel fouten en vertoonden niet het gebruikelijke lineaire verband
tussen reactietijd en oriëntatie van de stimulus dat de deelnemers met links HCP en de controlodeelnemers wel lieten zien. Geconcludeerd werd dan ook dat de beperkingen in motorisch vooruitplannen bij het grijpen van objecten van mensen met rechts HCP (mede) veroorzaakt worden door beperkingen in het vermogen tot motor imagery.

Tot besluit, de goedgecontroleerde studies beschreven in dit proefschrift dragen bij aan een groter inzicht in motorisch vooruitplannen bij mensen met HCP. Door verschillende aspecten hiervan te onderzoeken, is aangetoond dat mensen met (rechts) HCP beperkingen in bewegingsplanning hebben, in plaats van enkel een verstoring van de bewegingsuitvoering. Door beperkingen in het vermogen tot motor imagery aan te tonen bij mensen met rechts HCP, is een neurale proces blootgelegd dat (mede) verantwoordelijk lijkt te zijn voor de beperkingen in het vermogen tot motorisch vooruitplannen. Deze kennis heeft niet alleen theoretische waarde, maar kan tevens een nieuw licht werpen op verschillende bewegingsaspecten van mensen met HCP om op deze manier een bijdrage te leveren aan het optimaliseren van revalidatieprocessen.
Dankwoord
Dankwoord

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Dankwoord
Over de auteur/About the author


Marcel Mutsaarts was born on January 21st 1976 in Dommelen. In 1995 he commenced a psychology degree at the Radboud University Nijmegen (RUN). Marcel chose cognitive psychology as his main subject and graduated in the summer of 2000 with a psychomotor study on the shape of haptic space in grasping movements. In April 2001 he began his PhD-project, entitled ‘Adaptation in movement disorder’, at the Nijmegen Institute for Cognition and Information (NICI), under supervision of Dr. Bert Steenbergen, Dr. Ruud Meulenbroek, and Prof. Dr. Harold Bekkering. This thesis is the results of research Marcel performed during the five years of his PhD-project. In addition to his primary work as a researcher, he followed a teachers program that resulted in a teaching certificate in 2006. On completion of his PhD-contract, Marcel began working as a teacher at the school of art therapy, at the Hogeschool of Arnhem and Nijmegen (HAN). He combined this position with a position of psychology teacher at the RUN. Marcel obtained a full teaching position at the HAN, starting September 2007.