Constraints on grip selection in hemiparetic cerebral palsy: effects of lesional side, end-point accuracy, and context

Bert Steenbergen a,∗, Ruud G.J. Meulenbroek a, David A. Rosenbaum b

a Nijmegen Institute for Cognition and Information, University of Nijmegen, P.O. Box 9104, 6500 HE, Nijmegen, The Netherlands
b Department of Psychology, 642 Moore Building, Pennsylvania State University, University Park, PA, 16802, USA

Accepted 4 November 2003

Abstract

This study was concerned with selection criteria used for grip planning in adolescents with left or right hemiparetic cerebral palsy. In the first experiment, we asked participants to pick up a pencil and place the tip in a pre-defined target region. We varied the size of the target to test the hypothesis that increased end-point precision demands would favour the use of a grip that affords end-state comfort. In the second experiment, we studied grip planning in three task contexts that were chosen to let us test the hypothesis that a more functional task context would likewise promote the end-state comfort effect. When movements were performed with the impaired hand, we found that participants with right hemiparesis (i.e., left brain damage) aimed for postural comfort at the start rather than at the end of the object-manipulation phase in both experiments. By contrast, participants with left hemiparesis (i.e., right brain damage) did not favour a particular selection criterion with the impaired hand in the first experiment, but aimed for postural comfort at the start in the second experiment. When movements were performed with the unimpaired hand, grip selection criteria again differed for right and left hemiparetic participants. Participants with right hemiparesis did not favour a particular selection criterion with the unimpaired hand in the first experiment and only showed the end-state comfort effect in the most functional tasks of the second experiment. By contrast, participants with left hemiparesis showed the end-state comfort effect in all conditions of both experiments. These data suggest that the left hemisphere plays a special role in action planning, as has been recognized before, and that one of the deficits accompanying left brain damage is a deficit in forward movement planning, which has not been recognized before. Our findings have both theoretical and clinical implications.

1. Introduction

When individuals with hemiparetic cerebral palsy are asked to grasp an object with the impaired arm, a characteristic movement pattern is observed. The movement pattern is distinguished by an increased number of submovements (e.g., Refs. [51,52]), increased variability of hand trajectories (e.g., Refs. [56,57]), inappropriately coordinated force levels in the hand and fingers (e.g., Refs. [7,8]), a stereotyped shoulder–elbow recruitment order (e.g., Refs. [24,47]), and an increased level of trunk involvement (e.g., Refs. [1,3,55]). Movement patterns observed when the same subjects perform with the unimpaired hand also show some deviations from movement patterns exhibited by normal controls (e.g., Refs. [2,10,18]).

The cause of the movement pattern specific to hemiparetic cerebral palsy has been ascribed to damage to the mechanisms underlying movement execution. This ascription is reasonable considering that the primary motor cortex, which is crucially involved in movement execution, is often damaged in hemiparesis. Thus, it is unsurprising that hemiparesis has classically been referred to as an “upper motor neuron syndrome” (cf. Ref. [19]). As compelling as this analysis may be, however, because cortical areas such as the dorsolateral frontal, premotor cortex, and supplementary motor area are close to the primary motor cortex, it is also possible that when these more frontal cortical areas are damaged during the onset
of hemiparesis, their associated functions—goal selection, sequencing, and motion planning [60]—are also affected. If this hypothesis is correct, the implication is that hemiparetic cerebral palsy reflects disorders of processes antecedent to, and so "higher than," movement execution per se.

The present study was designed to test this hypothesis by evaluating the extent to which people with hemiparetic cerebral palsy show signs of abnormal motion planning. Because the study was behavioral, it only provided a test of the behavioral hypothesis offered here. Still, it is possible to speculate on the neural substrates of the behavior in interpreting the results, just as it was possible to motivate this behavioral inquiry by considerations of neuroanatomy and neurophysiology. We offer such speculations in the final section of the article.

In approaching the question of how motion planning works in individuals with hemiparetic cerebral palsy, it is important to focus on some type of motion that is sensitive to planning effects. A good candidate is prehension. Prehension requires motion planning to permit adaptive modification of grasps depending on what objects are grasped and for what purpose [25]. Initial grasps generally ensure that, when an object needs to be moved to a new position, the task ends with the upper extremity in a comfortable final posture (i.e., a posture for which the joints end at or near the middle of the range of motion) [4]. Rosenbaum et al. [30,31,34] found that the preference for ending near midrange applies to the termination of complex object transport maneuvers. In particular, these authors discovered that when people reached out and took hold of a cylinder that had to be moved to another location, they usually took hold of the cylinder with an awkward hand posture (i.e., with an underhand grip) if this enabled them to complete the cylinder transport with a comfortable posture (i.e., with an overhand grip). This "end-state comfort effect" has been observed in a wide variety of bar-transport and handle-rotation tasks [9,29–32,34,40,41]. The end-state comfort effect indicates that subjects plan beyond the first grip and anticipate future states.

Rosenbaum et al. [34] proposed three explanations for the end-state comfort effect: (1) exploitation of gravity, (2) use of elastic energy, and (3) precision. According to the latter explanation, movements at or near the middle of the range of motion of a joint can be performed with greater precision than movements at or near extreme joint angles. Consistent with this hypothesis Rosenbaum et al. [34] showed that pronation–supination oscillations of the sort required to make corrective movements occur more rapidly at or near the middle of the forearm’s pronation–supination range than at the extremes, and Rossetti et al. [36] showed less in pointing variability at mid-range joint angles than at extreme joint angles.

Recently, Steenbergen et al. [46] tested whether end-state comfort also functions as a selection criterion in grip planning for people with spastic hemiparesis. These authors anticipated that as a result of the reduced range of motion on the impaired side due to hyperactive stretch reflexes and hypertonia accompanying spasticity, there would only be a small joint range in which reliable position-error encoding exists. This prediction was tested both in a bar-positioning task and a bar-rotation task. The question was whether the observed grasping movements reflected constraint satisfaction with respect to postural comfort at the start of the movements, at the end of the movements, or during the movement. Constraint satisfaction that was defined with respect to postural comfort during the movement was operationalised as minimization of the sum of forearm pronation and supination (termed "total comfort" in what follows). The results indicated that for the impaired hand, end-state comfort was not a selection criterion for grip planning. Rather, the results suggested that grip selection was either determined by start-posture comfort or total comfort (i.e., the tendency to minimize forearm rotation). Limitations in the design of that study made it impossible to distinguish between the latter two hypotheses.

In the two experiments described here, we followed up on the earlier study of Steenbergen et al. [46] by seeking to identify the grip-planning selection criteria used by people with hemiparetic cerebral palsy. For this purpose, we studied bar-handling tasks in which we manipulated two experimental factors: end-point precision (Experiment 1) and task context (Experiment 2). We also examined differences between left- and right-brain damage participants to gain more insight into the hemispheric control of grip planning. Our interest in the differential effects of damage to the left or right side of the brain was prompted by earlier work suggesting that brain regions devoted to movement planning are primarily located in the left hemisphere. That work began with the classic observations concerning planning deficits in apraxia by Liepmann (see Freeman [11] for a review). More recently, the special role of the left hemisphere for motor planning has been confirmed by Schluter et al. [39], using PET, who showed activation in the prefrontal, premotor, and intraparietal areas of the left hemisphere but not the right hemisphere during choice reaction time tasks, irrespective of the hand performing the responses. The findings of Schluter et al. (2001) are consistent with the work on apraxia in suggesting that the areas responsible for movement planning are mainly located in the left hemisphere (e.g., Refs. [12,14,17,49,59]). Based on findings such as these, we hypothesized that movement planning, as indexed by the end-state comfort effect, would be less adversely affected by damage to the right hemisphere than by damage to the left hemisphere in individuals whose neurological conditions are otherwise comparable. We tested this prediction by comparing the grasping movements of adolescents with left and right hemiparetic cerebral palsy.
2. Experiment 1

In the first experiment, we varied end-point precision demands to see whether this factor would increase the likelihood of comfortable end postures on the unimpaired side. We asked participants to pick up a pencil that lay on a cradle that stood on a table. The cradle was positioned in front of the participants’ body midlines. The participants were asked to pick up the pencil and use the tip to place a dot inside a small or large circle on a sheet of paper lying on the table. The initial direction of the pencil tip (either leftward or rightward) and the initial hand orientation imposed at the start of each trial (palm up, down, or sideways) were manipulated. Specific combinations of these conditions allowed us to determine whether the way the pencil was grasped reflected planning with respect to start-posture comfort, end-posture comfort, or total comfort. By asking participants to perform this task both with the impaired and unimpaired hand, we could determine whether these three possible planning criteria determined grip selection more for one hand than the other. We hypothesized that limitations in the extent of forward planning for the impaired hand would be reflected in start-posture comfort for that hand, whereas the less limited extent of forward planning for the unimpaired hand would be associated with end-posture comfort for that other hand.

2.1. Method

2.1.1. Participants

Eleven participants with hemiparetic cerebral palsy participated on a voluntary basis. All participants were students at the Mariëndael School for Special Education in Arnhem. Selection of the participants was based on information in school records and from personal tutors made available with full permission of the participants. As the hemiparetic participants were students of a school rather than patients in a medical clinic, information about their individual neuropathology was limited. Only individuals known not to suffer from hemi-neglect or apraxia were included in the study. In addition, the only individuals who were selected were diagnosed with unilateral brain damage that resulted in spastic hemiparesis. All had functional sitting balance and had the attentional and cognitive capacities to perform the experiment. The age of the participants ranged from 13 to 19 years (mean, 16 years, 4 months; S.D. 1 year, 8 months). Six participants suffered from right spastic hemiparesis. The other five had left spastic hemiparesis. All had undergone extensive rehabilitation programs and their situations were described by their teachers as stable. At the time of testing, some subjects received physical therapy aimed at pain relief and preventing contractures. Information about the participants is given in Table 1.

2.1.1.1. Apparatus, task, experimental procedure, and instructions. The experimental set-up is shown in Fig. 1. Participants were seated comfortably at a table upon which was placed a cradle at a distance of 15 cm from the participant. Prior to each trial, a pencil (diameter 3.5 cm, length 27 cm) was set on the cradle, such that it was 8 cm above the table surface. This set-up allowed participants to place their hands beneath the pencil to permit a palm-up start posture (see below). A white sheet of paper (21 x 21 cm) on which a circle was drawn was placed either to the left or to the right of the cradle depending on the hand that was used. The center of the circle was 35 cm from the edge of the table closest to the participant. The diameter of the circle was either 3.5 or 0.6 cm. Two blue sheets of paper (10 x 10 cm) placed at the table edge closest to the participant on the left or on the right of the participant served as starting locations for the two hands.

Participants began each trial with the hand resting in a prescribed orientation before reaching out to pick up the pencil and use it to place a dot within the designated circle. Initial hand orientation was introduced as an independent
variable so we could distinguish among the impact of the three grip selection criteria, viz., start-posture comfort, end-posture comfort, or total comfort. Three prescribed hand orientations were used (see Fig. 2): palm up (90° supination from neutral), palm down (90° pronation from neutral), or neutral (lateral side of the hand resting on the table top and thumb pointing up). Three test trials were run with the unimpaired arm at the start of the experiment. In these test trials, the experimenter also showed alternative possibilities for task execution. The participants were asked to imitate the three prescribed hand orientations as well as the alternative task solutions. Participants who were unable to imitate the prescribed hand orientations were relieved from further testing.

Fig. 2. Examples of the three initial, resting, hand orientations (A), two start postures (B), and two end postures (C). (A) From top to bottom: palm down, palm up, and neutral. (B) From top to bottom: overhand and underhand. (C) From top to bottom: thumb up and thumb down. Note that, in these figures, a marker is grasped and not the pencil used in Experiment 1.
Two start postures were distinguished at the moment the pencil was grasped: an overhand posture or an underhand posture (see Fig. 2). Two end postures were also distinguished. End posture was defined as the posture of the hand at the end of the task (viz., at dot placement). One end posture had the thumb pointing up. The other had the thumb pointing down (see Fig. 2).

During the task, no speed demands were imposed. It was stressed, however, that the dot was to be placed as precisely as possible within the circle and that the grip that was used should remain unaltered once the pencil was picked up.

The following variables were manipulated: hand used (impaired or unimpaired), prescribed hand orientation (palm up, down, or neutral), circle diameter (0.6 or 3.5 cm), and pencil tip direction (left or right). Crossing these factors resulted in a total of 24 conditions. Each participant performed 10 consecutive trials in each condition, resulting in a total of 240 trials per participant. The experiment was performed in 4 blocks of 60 trials each. Within a block the factors hand used and circle diameter were unaltered, whereas pencil tip direction and prescribed hand orientation were randomised. In addition, the order of the four blocks was randomised across participants, with the restriction that every participant started with a block in which the unimpaired hand was used. This was done to prevent discouragement as might have occurred had the experiment begun with the impaired hand. The complete experimental session was recorded on videotape and lasted about 1 h. Resting periods were introduced between the four blocks and upon the participants’ request. All participants gave signed consent prior to testing.

2.1.1.2. Data reduction. Analysis of the video recordings was performed off-line. The variables of interest in each trial were start posture, end posture, and total comfort. Both start posture and end posture were directly scored from the video recordings (see Fig. 2). Total comfort was scored as follows. First, as in Steenbergen et al. [46], we determined for each of the 24 conditions separately the theoretically possible ways in which the task could be performed, bearing in mind the biomechanical limits of forearm pronation and supination. For each such theoretically possible task solution, we calculated the total amount of forearm rotation needed (i.e., the sum of forearm pronation and supination). Second, for each condition separately, we compared these theoretical task solutions with the actual task solution that was chosen by the participants. The actual task solution was scored directly from the video recordings. This enabled us to infer for each condition whether participants chose a task solution aimed at total comfort, i.e., minimizing the total amount of forearm rotation. For example, consider the condition in which the prescribed initial hand orientation of the right hand has the palm facing upwards while the pen tip points to the left. In this case, two task solutions are possible. In the first task solution, the pen is grasped with an underhand start grip (i.e., palm facing upwards), as seen in Fig. 2. In this case, the forearm does not need to rotate to grip the pencil. However, to place a dot on the paper, the forearm needs to make a $90^\circ$ pronation movement. Choosing this task solution leads to an uncomfortable start posture, a comfortable end posture, and necessitates a total of $90^\circ$ forearm rotation. In the second task solution, the pen is grasped with an overhand grip (i.e., with the palm down), in which case the forearm first needs to be pronated $180^\circ$ to grasp the pen and then the forearm needs to be pronated another $90^\circ$ to place the dot on the paper. Choosing this task solution leads to an uncomfortable start posture, an uncomfortable end posture, and necessitates a total of $270^\circ$ forearm rotation.

How can we infer from this example which selection criterion was used? Suppose we want to find out whether a participant strives for postural comfort at the end of the task. In that case, the participant should chose the first task solution over the second, as the first would leave the hand in a...
comfortable posture at the end of the task. However, it might be argued that total comfort actually governs this solution because the total amount of forearm rotation is less in the first task solution (90°) than in the second (270°). This indicates that, at least for this outcome, the interpretation of which criterion is used is ambiguous.

Alternatively, suppose the participant strives for start posture comfort in this condition. In that case, the second task solution is chosen over the first because the second task solution leads to an uncomfortable end posture. This condition also induces more forearm rotation than does the first task solution, in which case the interpretation of which criterion is used (from the three we introduced) is unambiguous.

This pair of outcomes and the interpretations that can be assigned to them illustrates what we call a critical task condition. A critical task condition for any given criterion (start posture comfort, end posture comfort, or total comfort) is one that unambiguously provides evidence for the criterion if behavior is exhibited that is consistent with it. The example just described illustrates a critical task condition for start posture comfort but not for end-posture comfort or total comfort. If start posture comfort were manifested in this condition, therefore, start posture comfort would be the only criterion from the set of three under consideration that could be inferred.

Table 2 shows which selection criteria could determine the various grip types in the conditions of Experiment 1. The conditions are collapsed across circle size. In some conditions, any of the three criteria can account for the selected grip. For example, if the pen tip points to the left, the palm is down at the start, and the left hand is used, then aiming for start posture comfort (the upper left block in Table 2) also leads to end posture comfort (indicated with ‘= End’ in Table 2) as well as total comfort (indicated with ‘= Total’ in Table 2). By contrast, in other conditions, two of the three criteria could underlie the choices. For example, if the pen tip points to the left, the palm is up at the start, and the left hand is used, then aiming for end posture comfort (the block in the second column and third row of Table 2) also leads to start posture comfort (indicated with ‘≠ Start’ in Table 2) but not to total comfort (indicated with ‘≠ Total’ in Table 2). In a third series of conditions, the so-called critical task conditions, only a single criterion can be held responsible for the selected grip type. For example, if the pen tip points to the right, the palm is down at the start, and the left hand is used, then aiming for end posture comfort (the block in the second column and fourth row of Table 2) excludes aiming for start posture comfort (indicated with ‘≠ Start’ in Table 2) as well as total comfort (indicated with ‘≠ Total’ in Table 2). These critical task conditions are most informative for the present research.

Table 2 shows that in some conditions identical combinations of selection criteria could have been responsible for the observed grip types. Specifically, the nine cells in the lower right corner have identical combinations of selection criteria as the nine cells in the upper right corner. Likewise, the nine cells in the upper right corner have identical combinations of selection criteria as the nine cells in the lower left corner. Grouping these cells (and collapsing across circle size) results in six conditions with unique combinations of the selection criteria.

To analyse the incidence of the start-posture, end-posture, and total-comfort grip selection criteria, the data in each condition were pooled across all participants and repetitions and analysed by a non-parametric chi-square procedure. In the first analysis, a series of chi-square tests

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Hand posture at start of trial</th>
<th>Applied selection criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pen-tip direction</td>
<td>Hand used</td>
<td>Start comfort</td>
</tr>
<tr>
<td>Leftward</td>
<td>Palm down</td>
<td>= End = Total</td>
</tr>
<tr>
<td>Neutral</td>
<td>Palm up</td>
<td>= End ≠Start ≠Total</td>
</tr>
<tr>
<td>Rightward</td>
<td>Palm down</td>
<td>≠End ≠Total</td>
</tr>
<tr>
<td>Neutral</td>
<td>Palm up</td>
<td>≠End ≠Total</td>
</tr>
</tbody>
</table>

Conditions are uniquely specified by three pointing directions of the pen and three prescribed hand postures at the start of the trial. For example, in the upper right block, if total comfort is the applied selection criterion this also leads to a comfortable start posture [≠Start], but not to a comfortable end posture [≠End]. ‘Critical task conditions’ for each of the three selection criteria are underlined. In these conditions, only a single criterion can be held responsible for the selected grip type. For example, the block on the first row of the fifth column is a critical task condition for end posture comfort when the task is performed with the right hand. Aiming for end posture comfort in this condition excludes aiming for start comfort [≠ Start] and total comfort [≠ Total].
was performed separately for each condition on start-posture comfort, end-posture comfort, and total comfort (36 comparisons in total). Second, to determine the differences related to the side of the cerebral damage, we repeated the analyses for both groups separately (i.e., left and right hemiparesis, 72 comparisons in total). Third, to analyze actual end-point precision, we scored placement of the dots on the paper. Dots placed on or inside the circle line were scored as correct whereas dots placed outside the circle line were scored as incorrect. Placement of the dots was operationalised as the first contact of the pencil tip with the paper surface. Correction of the dot after first placement outside the circle was also scored as incorrect. A chi-square procedure was used to analyse the precision of dot placement (correct, incorrect: eight comparisons in total).

Because multiple comparisons were performed on the same data set, we used the Bonferroni correction to ensure that the overall chance of making a type I error remained less than 0.05. The Bonferroni correction procedure entails dividing \( \alpha \) by the number of comparisons that are made.

### 2.2. Results

#### 2.2.1. Qualitative results

As expected, task completion with the impaired hand took longer than task completion with the unimpaired hand. In addition, participants made more slips on the paper with the impaired hand than with the unimpaired hand. Moreover, the dots were larger with the impaired hand than with the unimpaired hand due to the increased force exerted with the impaired hand. Fig. 3 gives examples of dot placements for the large and small circle and for the unimpaired and impaired hand.

#### 2.2.2. Quantitative results

A preliminary analysis of the data showed no effects of target circle size. Therefore, the data were collapsed across this variable.

#### 2.2.3. Grip-type selection criteria: overall results

Table 3 shows the number of times the three grip-type selection criteria were applied in the six conditions for the unimpaired hand and the impaired hand separately. A total of 36 comparisons were made, requiring an adjusted \( \alpha \) level of \( 0.05/36 = 0.0014 \).

##### 2.2.3.1. Unimpaired hand

Table 3 shows that the unimpaired hand ended with a comfortable posture in all six conditions. The relevant values of \( \chi^2 \) (1, \( n = 220 \)) ranged from 29.1 to 220, all \( p < 0.0014 \). The critical-task-condition chi-square for end-posture comfort was significant, \( \chi^2 (1, n = 220) = 29.1, p < 0.0014 \), but was not significant for start posture comfort (sixth row and first column of Table 3) or total comfort (third row and third column of Table 3). Hence, the participants strove for end-posture comfort when planning grips with the unimpaired hand.

##### 2.2.3.2. Impaired hand

In contrast to the unimpaired hand, the selection criterion that was used for the impaired hand was start-posture comfort. This proved to be

---

**Table 3**

Incidence of the 3 grip-type selection criteria in the conditions of Experiment 1 (see Table 2 for the conditions) collapsed over all 11 participants, 10 trials, and 2 circle sizes (i.e., 220 observations per cell).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Start comfort</th>
<th>End comfort</th>
<th>Total comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unimpaired hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impaired hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Critical conditions are underlined and bold values are significant at the adjusted \( p \)-level of 0.0014.

---

Fig. 3. Examples of dot placement at the end of the task, with the unimpaired hand for the large circle (A: 10 correct placements) and small circle (B: 9 correct placements, 1 incorrect placement), and with the impaired hand for the large circle (C: 9 correct placements, 1 incorrect placement) and small circle (D: 3 correct placements, 7 incorrect placements).
significant in all conditions, with values of $\chi^2 (1, n = 220)$ ranging from 45.5 to 220, all $p < 0.0014$. For start-posture comfort, the critical task condition is presented in the sixth row of the first column in Table 3. Here, start-posture comfort could be unambiguously inferred as the criterion for grip selection, $\chi^2 (1, n = 220) = 45.5$, $p < 0.0014$. The chi-square tests for the critical task conditions for end posture comfort (fourth row and second column of Table 3) and total comfort (third row and third column of Table 3) were not significant.

### 2.2.4. Grip-type selection: hemispheric differences

Whereas the foregoing analyses ignored issues pertaining to the side of cerebral damage, the analyses presented next focussed on this issue. Table 4 shows the results of the Chi-square analyses for the right hemiparetic group and for the left.
hemiparetic group separately. The adjusted alpha score level was set to 0.05/72 = 0.0007. Fig. 4 shows the percentage of adoption of a particular selection criterion in each of the corresponding critical task conditions for the right hemiparetic group and left hemiparetic group separately.

2.2.4.1. Unimpaired hand. Similar to the complete group analysis, planning for a comfortable end posture was significant in all conditions for the participants with left hemiparesis, with values of $\chi^2 (1, n=100)$ ranging from 36 to 100, all $p < 0.0007$. The outcome was different for the right hemiparetic participants. For this group, in five of the six conditions, planning for a comfortable end posture was significant, with values of $\chi^2 (1, n=120)$ ranging from 13.3 to 120, all $p < 0.0007$. However, the critical task condition chi-square for end-posture comfort was not significant (Table 4, fourth row and fifth column), nor was the critical task condition chi-square for start-posture comfort or for total comfort. Hence, participants with right hemiparesis did not exhibit a consistent strategy when using the unimpaired left hand.

2.2.4.2. Impaired hand. The results for the impaired hand of each group also deviated from the results of the complete group analysis. Table 4 shows that right hemiparetic participants planned for comfortable start postures in all conditions, with values of $\chi^2 (1, n=120)$, ranging from 53.3 to 120, $p < 0.0007$. The value in the critical task condition for comfortable start posture was $\chi^2 (1, n=120) = 53.3$, $p < 0.0007$, whereas the critical-task-condition chi-squares for comfortable end posture and total posture were not significant. The results for the left hemiparetic group were more variable, such that none of the critical-task-condition chi-square values was significant. Thus, when using the impaired hand, participants with left hemiparesis did not exhibit a consistent strategy.

2.2.5. Precision-demand effects

Although the grip-type selection criteria that were used did not differ when the target circle was small or large circle, we performed an analysis on the realized end-point precision with respect to placement of the dots. The $\alpha$ level was adjusted to 0.00625 (0.05/8 comparisons). Table 5 shows the number and percentage of dots placed inside the circle for the left and right hemiparetic participants separately. With the exception of the number of dots placed inside the small circle for the right hemiparetic participants with their impaired hand, all chi-square values were significant at $p < 0.00625$, indicating that more dots were placed inside the circle than outside. When participants with right hemiparesis had to place the dots inside the small circle with their impaired hand, the number of dots placed inside and outside the circle was equal. Thus, when dots were placed with the impaired hand, a difference was found between left and right hemiparetic participants. Whereas participants with left hemiparesis placed more dots inside the circles, participants with right hemiparesis failed to comply with the task instruction when the dots had to be placed inside the small circle.

2.3. Discussion

The first experiment yielded three main results. First, the participants exhibited a start-state comfort preference with the impaired hand. This outcome extends the results of Steenbergen et al. [46], who also found that with the impaired hand, hemiparetic subjects did not provide clear evidence for the end-state comfort effect. What was unclear from Steenbergen et al. [46] was whether hemiparetic subjects selected comfortable starting postures or tried to keep the total amount of joint rotation to a minimum. The analysis afforded by the present experiment disconfirmed the latter hypothesis (see Fig. 4). The present experiment also showed that the preference for start posture comfort depended on the side of the lesion. Participants with right hemiparesis selected a comfortable start posture with their impaired hand, but participants with left hemiparesis did not consistently prefer any of the three grip selection criteria despite a trend for comfortable start postures (see also Fig. 4).

Second, when treated as a group, the participants showed the end-state comfort effect with the unimpaired hand. This outcome replicates what was found before for normal individuals and suggests that hemiparetic individuals are capable of planning their movements in the same way as normal individuals do. However, differences were found again in the extent to which the end-state comfort effect was observed in the left and right hemiparetic participants. Whereas participants with left hemiparesis clearly aimed for end-posture comfort, participants with right hemiparesis did not consistently prefer any of the three grip selection criteria.

The third result was that circle size, and so required end-point precision, had no effect on the types of grips that participants adopted. Caution is required in interpreting this result because, in the small-circle condition, participants with right hemiparesis failed to comply with, or were unable to satisfy, the instruction to place the dots inside the circle with their impaired hand. When dots had to be placed inside the small circle with this hand, an even number of dots was placed inside and outside the circle.
Thus, the participants did not meet the end precision requirements of the task.

3. Experiment 2

In the second experiment, we examined the influence of task context on grip selection. As stated in Section 1, the majority of prehension movements require objects to be grasped for a particular purpose. One of the first studies that examined the influence of task context on the kinematics of a reaching movement was performed by Marteniuk et al. [25]. Their subjects picked up objects and either threw the objects into a large box or placed them into a tight fitting well. The deceleration phase of the transport movement was prolonged in the latter condition, suggesting anticipation of the precision demands of the upcoming act.

The effect of task context on the kinematics of the reaching movements in individuals with brain damage has been the focus of a large body of research, predominantly instigated from the applied field of occupational and physical therapy (e.g., Refs. [42,53,54,58,63,64,65]). The basic assumption in these studies is that task context might be an important determinant of the quality of movement performance in brain damaged individuals (cf. Ref. [50] Van der Weel et al., 1991). Task context has been varied in these studies either via manipulation of the functional specificity of the object (e.g., Refs. [28,53]), or via manipulation of the functional relevance of the task context, or embeddedness of the task in a natural sequence (e.g., Refs. [26,58]). Both manipulations of task context affected reaching performance in brain damaged individuals such that smoothness of moving was enhanced and movement speed increased when tasks were more functionally relevant or natural than when they were less so.

In Experiment 2, we examined the effects of task context on grip selection. Based on previous studies showing improved kinematics in more functional task contexts, we hypothesized that the end-state comfort effect would become more pronounced in the most functional task context. As in Experiment 1, we also examined differences pertaining to the side of the lesion.

3.1. Method

3.1.1. Participants

Ten participants, none of whom had participated in Experiment 1, volunteered to take part in the second experiment. The participants were diagnosed with spastic hemiparesis. They ranged in age from 14 to 19 years (mean, 17 years, 0 month; S.D. 1 year, 7 months). Five participants had left spastic hemiparesis, whereas the other five had right spastic hemiparesis (see Table 6 for additional participant information). All participants gave signed consent before testing. As was the case for the participants of Experiment 1, all the participants in Experiment 2 were students at the Mariëndael School for Special Education. The criteria for selecting participants were the same as in Experiment 1.

3.1.2. Task, apparatus, experimental procedure and instructions

The action that participants were asked to perform was picking up a cylindrical object, turning it over 180°, and then placing it at another location. This action was performed in three task contexts, which varied with respect to the functional specificity of the object to be manipulated and the extent to which the task was embedded in a functional setting. The first task context, denoted least functional, was similar to one that is generally used in experimental studies on grip planning (e.g., Refs. [30,46]). Participants picked up a bar and placed it upside down on another designated location. The second, more functional, task was to pick up a glass that lay upside down, invert it, and place it on a designated location as if water could be poured into it. In the third, most functional, task participants picked up the glass, turned it over, placed it down, and then poured water into it from a jar.

These actions were performed with the unimpaired hand as well as with the impaired hand, yielding a total of six conditions defined by task context (three levels) and hand used (two levels). In each condition, participants performed 6 consecutive trials, resulting in 36 trials in all. Experiments were blocked according to the factor hand used. Within a hand-used block, the order of the three task contexts was balanced across participants. As in Experiment 1, each participant started with the unimpaired hand.

Prior to testing, participants were seated comfortably at a table, upon which were placed the stimulus materials (the bar, glass, or glass and jar). Attached to the table top were two 21 × 15-cm sheets of paper. One sheet was blue and lay to the left of the subject. The other sheet was red and lay to the right of the subject. The sheets were 10 cm apart and were placed 5 cm from the edge of the table closest to the subject. These sheets were used as starting and placement locations of the objects, respectively.

Table 6

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age (year, month)</th>
<th>Hemiparesis</th>
<th>Aetiology</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>19.7</td>
<td>Right</td>
<td>Unknown</td>
<td>Nystagmus</td>
</tr>
<tr>
<td>2</td>
<td>Male</td>
<td>15.8</td>
<td>Right</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Female</td>
<td>17.2</td>
<td>Right</td>
<td>Cerebral palsy</td>
<td>Epileptic</td>
</tr>
<tr>
<td>4</td>
<td>Male</td>
<td>16.1</td>
<td>Left</td>
<td>Unknown</td>
<td>Epileptic</td>
</tr>
<tr>
<td>5</td>
<td>Male</td>
<td>19.7</td>
<td>Right</td>
<td>Cerebral palsy</td>
<td>Epileptic</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>17.3</td>
<td>Right</td>
<td>Cerebral palsy</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Female</td>
<td>14.1</td>
<td>Left</td>
<td>Cerebral palsy</td>
<td>Epileptic</td>
</tr>
<tr>
<td>8</td>
<td>Female</td>
<td>16.1</td>
<td>Left</td>
<td>Viral infection</td>
<td>Birth</td>
</tr>
<tr>
<td>9</td>
<td>Male</td>
<td>16.9</td>
<td>Left</td>
<td>Cerebral palsy</td>
<td>Epileptic</td>
</tr>
<tr>
<td>10</td>
<td>Female</td>
<td>17.1</td>
<td>Left</td>
<td>Cerebral palsy</td>
<td></td>
</tr>
</tbody>
</table>
depending on the hand that was used. The bar and glass that were used had similar dimensions and weight. For the bar, the relevant values were length = 15 cm, diameter = 5 cm, and weight = 250 g. For the glass, the relevant values were length = 14.7 cm, diameter = 5.4 cm, and weight = 240 g. The jar contained one cup (1 cp., volume of approximately 25 cl.) of water but could hold five cups.

At the start of each trial, the bar or glass was placed in the position that required subsequent inversion. Instructions were read out prior to testing, and the experimenter demonstrated the tasks to the participants, who were asked to imitate them. All participants were able to do this. No speed demands were imposed. Participants were instructed not to alter their grip after taking hold of the bar or glass. The experiment lasted half an hour.

3.1.3. Data reduction

The experiment was video-taped and analysed off line. The main variable of interest was the type of grip subjects used to pick up the bar or glass. For data-recording purposes, we assumed that there were just two start grips—thumb up (the “comfortable start posture”) or thumb down (the “uncomfortable start posture”). Similarly, and as a consequence, the same two grips were recorded for the end position—thumb up (when the object was initially picked up with an uncomfortable grip) or thumb down (when the object was initially picked up with a comfortable grip).

We performed several chi-square comparisons on the grip data to uncover effects of task context, side of hemiparesis, and severity of hemiparesis. A total of 10 comparisons were performed, yielding an adjusted alpha level of 0.005. Preliminary analyses showed that for the impaired hand the grip that was adopted could not be accounted for by the end-state comfort effect, nor was it affected by task context in any participant. We therefore focussed on the unimpaired hand, performing three kinds of data analysis for it. First, we compared the three task conditions for the whole group to uncover effects of task context on end-posture planning. Second, we analysed the difference between left and right hemiparetics (see Table 7). The chi-square values for tests of differences in the frequency of comfortable end postures for the two groups were as follows: \( \chi^2 (1, n = 60) = 9.93, p < 0.005 \), for context 1; \( \chi^2 (1, n = 60) = 1.46 \), not significant for context 2; and \( \chi^2 (1, n = 60) = 3.16 \), not significant for context 3. Thus, only in context 1 was a significant difference found between the left and right hemiparetic groups. In context 1, the left hemiparetic participants ended in a comfortable posture in 90% of the trials. By contrast, in this same context, the right hemiparetic participants ended in a comfortable posture at a rate that was statistically indistinguishable from chance (53% of trials). In contexts 2 and 3, participants from both groups ended significantly more often with a comfortable posture than with an uncomfortable posture. As seen in Table 7, the rates of ending comfortably were 93% and 83% for the left and right hemiparetics,

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Grips employed in the three conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task context</td>
<td>Unimpaired hand</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Right hemiparesis</strong></td>
<td></td>
</tr>
<tr>
<td>Subject</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Frequency</td>
<td>16</td>
</tr>
<tr>
<td>Percentage</td>
<td>53</td>
</tr>
<tr>
<td><strong>Left hemiparesis</strong></td>
<td></td>
</tr>
<tr>
<td>Subject</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Frequency</td>
<td>27</td>
</tr>
<tr>
<td>Percentage</td>
<td>90</td>
</tr>
</tbody>
</table>

A distinction is made between right and left hemiparesis and between the unimpaired hand and impaired hand. Bold values indicate significance at the adjusted \( p \)-level of 0.005 for end posture comfort.

3.2. Results

3.2.1. Task context: overall results

There was a difference in the occurrence of comfortable end postures among the three task contexts, \( \chi^2 (2, n = 180) = 15.69, p < 0.005 \). To identify the source of this effect, we compared the three contexts in a pairwise fashion. Context 1 differed significantly from context 3, \( \chi^2 (1, n = 120) = 14.07, p < 0.005 \). However, neither context 1 nor context 3 differed significantly from context 2 (\( \chi^2 \) values of 5.21 and 3.00, respectively).

3.2.2. Task context: hemispheric differences

To examine possible differences pertaining to the side of the cerebral damage, we analysed for each condition separately, the occurrence of comfortable end postures among left and right hemiparetics (see Table 7). The chi-square values for tests of differences in the frequency of comfortable end postures for the two groups were as follows: \( \chi^2 (1, n = 60) = 9.93, p < 0.005 \), for context 1; \( \chi^2 (1, n = 60) = 1.46 \), not significant for context 2; and \( \chi^2 (1, n = 60) = 3.16 \), not significant for context 3. Thus, only in context 1 was a significant difference found between the left and right hemiparetic groups. In context 1, the left hemiparetic participants ended in a comfortable posture in 90% of the trials. By contrast, in this same context, the right hemiparetic participants ended in a comfortable posture at a rate that was statistically indistinguishable from chance (53% of trials). In contexts 2 and 3, participants from both groups ended significantly more often with a comfortable posture than with an uncomfortable posture. As seen in Table 7, the rates of ending comfortably were 93% and 83% for the left and right hemiparetics,
respectively, in context 2, and 100% and 93% for the left and right hemiparetics, respectively, in context 3. Thus, end posture planning was apparent both for the left and right hemiparetic participants when the task context was more functional (contexts 2 and 3), but end posture planning was apparent for the left hemiparetics but not for the right hemiparetics when the task context was least functional (context 1). For the right hemiparetics, no consistent planning principle seemed to hold. Apparently, then, damage to the left hemisphere, which is manifested in a general way by right hemiparesis, led to deficient (or inconsistent) planning when the task context was relatively non-functional.

3.2.3. Task context: differences pertaining to the severity of the disorder

As shown in Table 7, participants with right hemiparesis were more severely affected than were participants with left hemiparesis. In the former group, three of the five participants were unable to perform the task with the impaired hand, whereas this was only the case for one participant in the left hemiparetic group. To examine the potential confounding effect of severity of hemiparesis on grip planning, we examined for each condition separately the occurrence of comfortable end postures as a function of severity of the disorder. The analysis indicated that severity of the disorder did not significantly affect grip selection. The relevant statistics were $\chi^2 (1, n=60) = 3.50$, not significant for condition 1; $\chi^2 (1, n=60) = 0.03$, not significant for condition 2; and $\chi^2 (1, n=60) = 0.51$, not significant for condition 3.

3.3. Discussion

The second experiment yielded four main results. First, planning with the impaired hand was not aimed at end-state comfort, nor was it affected by task context. Second, participants with left spastic hemiparesis planned for comfortable end postures in all three-task contexts with their unimpaired hand. Third, with their unimpaired hand, participants with right spastic hemiparesis planned for comfortable end postures only in contexts 2 and 3. By contrast, in context 1, participants with right hemiparesis did not behave as if they relied predominantly on any one planning constraint. Fourth, severity of hemiparesis did not account for the second and third result.

4. General discussion

The background for this study was that neurologically normal individuals generally try to end in a comfortable posture when they grasp objects [32], but individuals with spastic hemiparesis use other selection criteria for choosing grips [18,46]. Here, we further examined grip selection in hemiparesis by altering the task via manipulation of endpoint accuracy demands (Experiment 1) and task functionality (Experiment 2). We also analyzed the grip selection strategies for the impaired and unimpaired hands in left and right hemiparetics to explore the role of the left and right side of the brain in motion planning.

Collectively, the present findings suggest that planning with the unimpaired hand in individuals with hemiparesis is not disturbed per se, but instead is critically dependent on the task context. When analyzed as a group, participants with hemiparesis anticipated the future posture of the unimpaired hand when first grasping the object in a more functional task and in a task that demanded higher end-point precision. However, differences pertaining to the side of the lesion were found.

Earlier in this article, we hypothesized that aiming for end-state comfort may be beneficial for the signal-to-noise-ratio of position-error signals processed at the end of the task, in turn allowing greater precision when the dot was placed on the paper (cf. Refs. [16,36]). Consistent with this hypothesis, the results of Experiment 1 suggest that if end-point precision must increase, individuals with left hemiparesis (i.e., right hemisphere damage) used the same grip selection criterion (viz., end-posture comfort) as individuals without movement disorders when using their preferred hand. By contrast, participants with right hemiparesis (i.e., left hemisphere damage) did not anticipate the future posture of the unimpaired hand when first grasping the object. In the critical task conditions of Experiment 1 it appeared that start-posture comfort, end-posture comfort, and keeping the amount of forearm rotation to a minimum were aimed for equally often. Nevertheless, participants with right hemiparesis were still able to comply with the task instruction. That is, they placed all dots within the circle when using the unimpaired hand. Moreover, in the first task of the second experiment, participants with right hemiparesis did not significantly end the task more often in a comfortable end posture, which they did in the more meaningful tasks (tasks 2 and 3). Taken together, these findings show that planning for comfortable end postures is task-dependent in more subtle ways than has been recognized before.

Damage to the left hemisphere, and in particular the left parietal lobe, often leads to ideomotor apraxia (e.g., Ref. [49]). Evidence from gesture imitation suggests that patients with ideomotor apraxia are unable to correctly reproduce final postures (e.g., Ref. [5]). In the present study, none of the participants was apraxic, as confirmed by the fact that in both experiments when the possible task solutions were demonstrated to the participants they were able to reproduce them. This leads us to suggest that the present findings cannot be ascribed to apraxia. Instead, we think our findings indicate that left hemisphere damage can lead to a planning deficit manifested in grip selection.

Corroborating the latter conclusion are recent studies suggesting left cerebral dominance for action selection (e.g., Refs. [37–38]). Rushworth et al. [37], testing left and right hemisphere patients and neurologically normal controls
on five different tasks, showed that the left hemisphere patients were particularly impaired in response selection tasks. Rushworth et al. concluded that left hemisphere deficits are best explained as an impairment in response selection rather than an impairment in sequencing. Left hemisphere lesions in the subjects of the Rushworth et al. study involved the dorsolateral frontal and parietal cortices, striatum, thalamus, and white matter fascicles. Errors in hand posture selection have also been reported in other studies with left brain damaged patients (e.g., Refs. [15,23]). At the same time, numerous studies have shown that control of the ipsilesional hand is abnormal after unilateral brain damage (e.g., Refs. [6,13,22,44,48,61]). The present study indicates that part of this abnormality extends to grip planning such that participants with left brain damage show abnormalities in grip planning with their unimpaired hand.

Besides observing hemispheric differences for planning with the unimpaired hand, we also found that left and right hemiparetic participants differed with respect to grip planning of the impaired hand. Whereas participants with right hemiparesis preferred start-posture comfort in both experiments, participants with left hemiparesis only did so in the second experiment. The preference for start-posture comfort of the impaired hand in participants with right hemiparesis might have been detrimental for task performance when the dots had to be placed inside the small circle in the first experiment. In this condition, end-point precision was compromised, as evidenced by an equal number of dots placed inside and outside the target circle. What might be the reason for this apparent lack of planning with the impaired hand?

At this stage, it is useful to recall that memory for actions is an essential element in motor planning. One way that the role of memory in action planning has been conceived is to hypothesize that end postures are selected by evaluating stored, memorized postures [33,35]. Conceivably, the memory base of stored postures is impaired in hemiparetic participants. However, indirect evidence against this idea comes from research by Johnson [20], who showed that CVA patients with acute hemiplegia retain the ability to accurately represent movements of both their healthy and paralysed limbs. More recently, Johnson et al. [21] studied the ability to internally represent actions involving both limbs in chronic hemiplegia. In four experiments, they showed that despite chronic limb immobility, hemiplegic patients showed no differences in their ability to represent actions of the contralesional or ipsilesional limb. These findings demonstrate that internal action representations persist even after years of limb disuse. Given these findings in both acute and chronic hemiplegic patients, we consider it unlikely that impaired representations of action or loss of stored posture representations in the participants of the present study caused their impairment in forward planning. Such a conclusion does not necessarily vitiate the entire posture-based motion planning theory of Rosenbaum et al. [33,35], however.

Another possible explanation for the lack of forward planning with the impaired hand might be the inability of the participants to achieve comfortable or controllable postures involving the impaired hand for the tasks we studied. This may be due to well-known sensory disturbances involving the muscular senses (e.g., Ref. [8]). We did not explicitly ask participants to rate the different postures on a scale from least awkward to most awkward. Therefore, the present study does not allow us to either verify or falsify this hypothesis. Nevertheless, our previous study on grip planning in these participants suggested that they were able to differentiate the degree of awkwardness among the different postures of the impaired hand [46]. It was apparent from that study that the palm up start posture was rated as extremely awkward. Therefore, it may be assumed that participants in the present study tried to avoid the prescribed palm up orientation as soon as possible in the action sequence. This implies that they would pick up the object with a comfortable start posture (i.e., palm down upon taking hold of the pencil). Again, this explanation does not completely match the results, for the critical task condition for start posture comfort was not significant for participants with left hemiparesis (see column 1 and row 6 in Table 4 for the impaired hand).

A final explanation for the lack of forward planning with the impaired hand may be sought in the forward planning model of Wolpert and Ghahramani [62]. Their model employs sensorimotor knowledge to predict particular motor events. According to the model, forward planning specifies the sensory feedback that will result from the change in effector state, and feedback from the sensory system is used to update predictions about its state. The applicability of this model here relates to the fact that the impaired side of hemiparetic individuals is known to have disturbances in the sensory system, in part owing to abnormal reflex activity (e.g., Refs. [8,45]). Owing to this sensory disturbance, the reliable updating of a change in state is hampered. A strategy to cope with this unreliable sensory updating may be to segment the complete action into its constituent elements. Said another way, participants may adapt to unreliable sensory updating by performing submovements sequentially without an overarching, integrative plan (much as novice piano players plan each small series of notes on their own). Evidence consistent with this interpretation has been obtained in a recent study of the kinematics of prehension for the impaired and unimpaired side in individuals with hemiparesis [43]. Future studies can examine this hypothesis in more detail. Such studies will need more detailed neurophysiological and clinical data about each participant than was possible here so that the observed behavior of each participant can be compared with his/her level of functional and neurological impairment. In the present study, we only examined group differences (i.e., left versus right hemiparetic participants) to look for general deviations in motion planning. The study of individual differences in motion planning will make it possible to tell whether the hypothesis advanced above provides an adequate account of performance.
4.1. Clinical implications

The results of the second experiment of this study indicate that an increase in the functional context of the task may facilitate forward planning in participants with left brain damage. More generally, rehabilitation research (physiotherapy as well as occupational therapy) has repeatedly shown that the use of added-purpose activity is more effective than rote exercise for increasing the active range of motion in disabled individuals (e.g., Refs. [42,54,63,66]). Nelson [27] suggested that a science of occupation should include “research investigating the relationships between the degree of structure in typical occupational forms (types of informational support or task constraints) and the degree of predictability in the occupational performances (functional motor performances)” (p. 635). The results of the present study indicate that functional motor performance is influenced by the informational support or constraints contained in the task. As such, they support Nelson’s model of occupation, because the model predicts that occupational form (informational support or task constraints) will elicit, guide, and structure subsequent human performance.

It was clear from the present results that a non-functional task (turning over a bar) may obscure the movement capacity of an individual with left cerebral damage. Therefore, at a diagnostic level, functional tasks need to be used to assess and evaluate functional performance of individuals with brain damage such that the validity of this evaluation is warranted. Furthermore, at an intervention level functional tasks should be used for rehabilitation. As observed in the present study, functional tasks provoke more consistent and “appropriate” movement behavior than non-functional tasks (see Refs. [42,66]). This finding may prove useful to physiotherapists when they set up training programs for rehabilitation of brain-damaged patients.

Acknowledgements

The authors thank the participants of this study. Marsha van Lanen and Sandra Brinkman are also thanked for their valuable help in data collection. This research was supported by a grant awarded by The Netherlands Organization for Scientific Research (NWO) to the first author for the research project Adaptation in Movement Disorder (016.005.062).

References

[22] D. Kimura, Acquisition of a motor skill after left-hemisphere damage, Brain 100 (1977) 527–542.