Spatial Coupling in Children with Hemiplegic Cerebral Palsy During Bimanual Circle and Line Drawing

M.J.M. Volman

The effect of amplitude incongruence (small circles–large circles) and form incongruence (circles–lines) on the performance of the affected and non-affected arm was examined in 12 children with hemiplegic cerebral palsy in bimanual rhythmic drawing tasks. Amplitude and form incongruence are assumed to be associated with aspects of movement execution and movement planning, respectively. The following questions were addressed: Does amplitude or form incongruence in bimanual coordination result in: (a) accommodation of the affected or non-affected arm, or both, (b) an increase of temporal variability of drawing movements of the affected or non-affected arm, and (c) a decrease of bimanual coordination stability? Form incongruence resulted in accommodation of both affected and non-affected arm in a similar way found in non-disabled participants. Despite this accommodation, the temporal variability of both affected and non-affected arm was increased, and coordination stability decreased, because the spatial trajectories of affected and non-affected arm were still rather dissimilar. Amplitude incongruence resulted in accommodation of either the affected arm (large circles required) or non-affected arm (small circles required), and in an increase or decrease of temporal variability of the affected arm, depending on the degree of spatial similarity of the trajectories of affected and non-affected arm. These findings suggest that in children with hemiplegic cerebral palsy aspects of movement execution, but not aspects of movement planning are affected by the “hemiplegic” condition.

Key Words: cerebral palsy, motor, bimanual, coordination, spatial constraints

Many activities of daily living (e.g., using a fork and knife, buttoning a shirt, tying shoes) require adequate and task-specific coordination between both hands. Children with hemiplegic cerebral palsy suffer from poor movement control and coordination of the limb contralateral to the lesion. Not only a lack of cortical inhibition of “lower” subcortical brain structures, resulting in symptoms of spasticity and hypertonia, but also a lack of cortical excitation of cortico-spinal pathways, resulting in muscle weakness, might contribute to this movement deficit (Katz & Rymer, 1989). Previous studies have shown that movements of the affected arm of hemiplegic children are characterized by general slowness, lack of accuracy,
and dysfluency (Steenbergen, van Thiel, Hulstijn, & Meulenbroek, 2000; Trombly, 1992; Volman, Wijnroks, & Vermeer, 2002a) and that these children suffer from a marked deficit in prehension control (Eliasson, Gordon, & Forssberg, 1992; Gordon, Lewis, Eliasson, & Duff, 2003; Steenbergen et al., 2000; Utley & Sugden, 1998). It is obvious that such a lack of control and coordination of the affected arm leads to limitations in everyday activities that require coordination of both hands. How the affected and non-affected arm influence each other during bimanual coupling is the focus of the present study.

**Temporal and Spatial Constraints in Bimanual Coordination**

Bimanual coordination has been studied extensively in non-disabled individuals. It is generally agreed that bimanual coupling is influenced by temporal and spatial constraints. With regard to temporal constraints, for example, individuals show a preferred tendency to couple the two limbs either in an in-phase or antiphase coordination mode during bimanual rhythmic coordination (Kelso, 1984). A robust finding in the literature is that in-phase or symmetric mirror-like bimanual movements (simultaneous activation of homologous muscle groups) are more stable and accurate than antiphase or asymmetric movements (simultaneous activation of nonhomologous muscle groups) (e.g., Carson et al., 1997; Kelso, Scholz, & Schöner, 1986; Schmidt, Shaw, & Turvey, 1993; Semjen, Summers, & Cattaert, 1995). Symmetry-breaking factors, such as manual dominance or attention, could act upon this bimanual coordination stability (Stucchi & Viviani, 1993; Swinnen, Jardin, & Meulenbroek, 1996; Treffner & Turvey, 1996).

Whereas research initially focused predominantly on temporal constraints, the role of spatial constraints has been addressed in a number of studies as well (e.g., Bogaerts & Swinnen, 2001; Franz, 1997; Franz, Zelaznik, & McCabe, 1991; Marteniuk, MacKenzie, & Baba, 1984; Sherwood, 1994a; Sherwood, 1994b; Spijkers & Heuer, 1995; Swinnen, Jardin, Verschueren et al., 1998; Swinnen, Young, Walter, & Serrien, 1991). If in a bimanual task the two hands have to draw figures with different spatial characteristics, spatial coupling or interference occurs in the sense that the spatial trajectories of one or both hands are being disturbed. Franz (1997) distinguished between two sources of spatial coupling, namely direction and amplitude. Simultaneously drawing lines of different amplitudes with both hands, as a first example of spatial interference, resulted in a tendency of left and right arm to accommodate the amplitude to each other (Franz, 1997; Sherwood, 1994a; Spijkers & Heuer, 1995; Swinnen et al., 1991). Simultaneously drawing figures with different form characteristics (i.e., lines and circles) with both hands, as a second example of spatial interference, resulted in circles becoming less circular and lines becoming less linear and more ellipsoid (Franz, 1997; Franze et al., 1991). This type of spatial coupling (different form) is considered to be related to parameters of direction (Franz, 1997). Noticeably, spatial coupling in case of different movement amplitudes appeared to be asymmetric in the sense that coupling was dominated by the dominant hand and the non-dominant hand was the one that adapted its amplitude most (Sherwood, 1994b), whereas this asymmetry in coupling between the hands was absent in simultaneously drawing circles and...
lines (Franz, 1997). Simultaneously drawing lines in a different direction (e.g., one line in the Y-dimension and the other in the X-dimension), as a third example of spatial interference, resulted in a disruption in the spatial form of both trajectories (Franz, 1997).

It has been suggested that spatial interference in bimanual coordination due to differences in amplitude of the two limbs can be related to bimanual coupling at the level of motor execution, whereas spatial interference due to differences in direction of the moving limbs is related more to the level of movement planning (Franz et al., 1996; Franz, 1997). There is converging evidence for such a dissociation of aspects of planning and execution in spatial coupling. A study on spatial coupling in amputees who reported experiencing a phantom limb revealed, for example, that, when one of the movements in a “bimanual” task was produced—subjectively—by the phantom limb in an orthogonal condition (i.e., different directions), spatial interference still occurred indicating that this spatial coupling effect was not due to biomechanical properties associated with the movement of the phantom finger (Franz & Ramachandran, 1998). Furthermore, other studies found that spatial interference due to differences in direction could not be modulated by manipulation of afferent information (Swinnen, Puttemans, Vangheluwe, et al., 2003), neither by loading-related modulations of muscle activity (Levin, Wenderoth, Steyvers, & Swinnen, 2003; Swinnen, Dounskaia, Levin, & Duysens, 2001). These findings suggest that spatial interference due to differences in direction primarily emerges from the abstract level of motor planning and can be dissociated from the level of motor execution. This hypothesis is supported by neurophysiological studies showing that direction information for movement is encoded by a population of neurons in the motor cortex (Georgopoulus, Schwartz, & Kettner, 1986; Schwartz, 1994), even for bimanual movements when the two arms move simultaneously in different directions (Steinberg, Donchin, Gribova, et al., 2002). The present study examined these different aspects of spatial coupling in children with hemiplegic cerebral palsy.

**Bimanual Coupling in Hemiplegic Cerebral Palsy**

Several studies investigated bimanual coordination in hemiplegic cerebral palsy children during goal-directed movements (Hung, Charles, & Gordon, 2004; Steenbergen, Hulstijn, de Vries, & Berger, 1996; Steenbergen et al., 2000; Sugden & Utley, 1995; Utley, Steenbergen, & Sugden, 2004; Utley & Sugden, 1998). Sugden and Utley (1995) studied reaching and grasping at “preferred speed” and reported that the way temporal coupling between the affected and non-affected arm was established was not unequivocal: either the affected or non-affected arm adapted its performance (i.e., movement speed) to that of the other one, or both arms adapted. In two other studies on bimanual reaching and grasping “at speed” it was, however, found that the coupling was dictated by the affected arm (i.e., the non-affected arm adapted to the speed level of the affected arm) not changing its performance compared to a unimanual control condition (Steenbergen et al., 1996; 2000). The temporal coupling decreased when accuracy demands for the affected arm were increased (Steenbergen et al., 1996). Utley and Sugden (1998) also studied reaching and grasping at speed, but used sequential tasks of increasing complexity (reach and touch; reach and grasp; reach, touch, and grasp). Findings
were similar to that of Steenbergen et al. (1996; 2000) only for the first part of the movement in which the bimanual coupling was tight and dictated by the affected arm. In the second part of the more complex sequential reach (touch) and grasp task, however, the bimanual coupling decreased because the affected arm more or less returned to its preferred speed of movement. Hung, Charles, and Gordon (2004) examined bimanual coupling using a sequential task in which both hands had a different role (opening a drawer with one hand and manipulating its contents with the other) under varying speed conditions. In contrast to control participants, bimanual coupling in hemiplegic children was hardly observed although coupling was facilitated in “fast” compared to “preferred speed” conditions. All in all, these studies show that bimanual coupling in the temporal domain is often—but not always—dictated by the affected arm, and that the nature of the coupling is also dependent of speed and accuracy demands, and task complexity. Furthermore, all studies reported large intra- and inter-individual differences.

One study examined bimanual coupling of affected and non-affected arm in children with hemiplegic cerebral palsy using a bimanual circle drawing paradigm (Volman, Wijnroks, & Vermeer, 2002b). Contrary to reaching and grasping tasks, bimanual circle drawing implies that the hand of participants is fixed on a pen stylus. Thus, asymmetries in bimanual coupling due to difficulties in prehension control can be ruled out. In this study, children performed bimanual circle drawing movements under symmetric or inphase (simultaneous activation of homologous muscle groups) and asymmetric or antiphase (simultaneous activation of nonhomologous muscle groups) conditions. Interestingly, it was found that in the symmetric coupling mode the performance of the affected arm enhanced (i.e., decrease of temporal variability) towards the performance level of the non-affected arm, whereas in the asymmetric mode bimanual coupling was dictated by the affected arm resulting in an increase of temporal variability of the non-affected arm. Considering the fact that in functional bimanual tasks the spatial demands for both hands are often asymmetric in nature, it remains to be seen whether this benefit from symmetric coupling is put in jeopardy in bimanual tasks that are symmetric with regard to temporal constraints, but asymmetric (i.e., incongruent) with regard to spatial constraints.

The aim of the present study was to investigate spatial coupling of the affected and non-affected arm in children with hemiplegic cerebral palsy during simultaneous drawing of circles or lines with both hands. Amplitude (i.e., small circle–large circle task) and form (i.e., circle-line task) were manipulated and accommodation of the affected and non-affected arm was measured. Accommodation in bimanual coordination refers to the intrinsic tendency of the motor system to produce the same spatial trajectories with both arms when the task requires the participant to perform spatially different trajectories with each arm. In the present study, accommodation was defined as the adaptation of the spatial trajectories of one limb (towards that of the other limb) in a “bimanual spatially incongruent condition” in comparison to a “single-handed control condition” (cf. Franz et al., 1997). The following research questions were addressed. First, does amplitude or form incongruence in bimanual coordination result in accommodation of the affected or non-affected arm, or both? Normally, one would expect that incongruence of amplitude leads to accommodation of the non-dominant arm (here, the affected arm) (cf. Sherwood, 1994b), but findings on temporal coupling in hemiplegic children show that it is predominantly the non-affected arm that accommodates. With regard to form incongruence it is
expected that accommodation of both affected and non-affected arm will occur, because specification of form is assumed to be more or less independent of the relative timing of muscle activation (Franz, 1997; Swinnen et al., 1998; Swinnen et al., 2001). Second, does amplitude or form incongruence lead to an increase of temporal and spatial variability of drawing movements of the non-affected and affected arm, and to a decrease in bimanual coordination stability? It was expected that form incongruence in particular would result in an increase of temporal variability in the affected or non-affected arm and a decrease of bimanual coordination stability, because simultaneous activation of homologous muscles is more jeopardized than in drawing circles of different amplitudes (amplitude incongruence).

**Method**

**Participants**

Two child rehabilitation specialists from Rehabilitation Centre “de Hoogstraat” and Children’s Hospital “Wilhelmina KinderZiekenhuis” in Utrecht, selected 22 children with hemiplegic cerebral palsy, taking into account the following inclusion (spastic hemiparesis; age between 8 and 14 years old), and exclusion criteria (ataxia, athetoid movements; mental retardation). Ten children (mean age: 10.6 years; \(SD\) 1.2) and their parents were willing to participate in the present study. All children suffered from mild or moderate congenital spastic hemiparesis (Ingram, 1984). They were living at home and were attending special or regular primary or secondary education. An additional criterion was that children had sufficient hand function to hold a pen in power grip (thumb opposed to fingers). Participant characteristics are presented in Table 1.

**Table 1  Participant Characteristics**

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (yrs)</th>
<th>Gender</th>
<th>Hemiplegic arm</th>
<th>Severity</th>
<th>Tonus</th>
<th>Aetiology</th>
</tr>
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<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>2</td>
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<td>M</td>
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<td>3</td>
</tr>
<tr>
<td>3</td>
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<td>F</td>
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<td>mild</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
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<td>F</td>
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<td>mild</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
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<td>F</td>
<td>left</td>
<td>mild</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>10.9</td>
<td>M</td>
<td>right</td>
<td>mild</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>11.0</td>
<td>M</td>
<td>left</td>
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<td>3</td>
</tr>
<tr>
<td>8</td>
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<td>M</td>
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<td>mild</td>
<td>0</td>
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<tr>
<td>9</td>
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<td>10</td>
<td>13.4</td>
<td>M</td>
<td>right</td>
<td>mild</td>
<td>+</td>
<td>4</td>
</tr>
</tbody>
</table>

*Note. Aetiology: 1, perinatal lack of oxygen; 2, asymmetric hydrocephalus; 3, perinatal cerebrovascular accident; 4, unknown. Tonus: 0, normal; +, increased.*
Apparatus and Setup

A digitizer (Wacom Intuos A3) and two cordless pens (Intuos GP 300) were used to register circle and line drawing movements on the hard drive of a PC (sample frequency 100 Hz; spatial accuracy ± 0.25 mm). The pen was mounted in a tube (length 17 cm; diameter 3 cm) covered with foam to enhance grip function. Children were seated at a table. A Tripp Trapp chair was used to individually adjust the position of the child relative to the table. Children were seated so that they had good support for their legs, and their breast was just above table height and close against the table. The position of the lower arm was parallel to the digitizer surface, while the angle between upper arm and digitizer was about 30°.

Tasks and Procedure

Two tasks were performed: a line task and a circle task. The circle task consisted of drawing continuous circles. The direction of movement was specified: movements of the left-hand in clockwise direction and of the right hand in a counter-clockwise direction. Thus, in bimanual circle tasks the hands moved mirror-wise (symmetric). The line task consisted of drawing reciprocal lines along the Y-dimension, also mirror-wise.

Children were instructed to hold the pen in power grip (thumb opposed to fingers) and perform the task with a “stiff” wrist. Templates (circle-circle, line-line, circle-line, or line-circle) were placed on the digitizer under a transparent overlay. The circle diameter was 9 or 17 cm, the line-Y length 9 cm, and the distance between the center of circle(s) or line(s) was 23 cm (Figure 1). Children were asked to perform the drawing tasks in a preferred tempo. They were instructed to maintain the same tempo as good as possible among the different task conditions. During the drawing task they had to fixate their eyes on a yellow marker (diameter 2 cm) placed at the upper side of the digitizer at the midline between the templates. The children started a trial when the experimenter had given a “go” signal and stopped after completion of 15 periodic movements of circles or lines. Participants performed 21 experimental trials. There was a short pause (30 seconds) between the trials and a 10-min break after 12 trials. The experiment lasted approximately 30 min.

Figure 1—Example of templates for the circle–line task (left panel) and large circle–small circle task (right panel).
Experimental Design

The experimental design was determined by the factors coupling condition (bimanual congruent, bimanual incongruent, single), form (circle, line), amplitude (9 cm, 17 cm), and arm (affected, non-affected). Bimanual congruent tasks (i.e., circle-circle and line-line) required simultaneous activation of homologous muscles. Experimental conditions are presented in Table 2. The experiment consisted of seven bimanual conditions. Four bimanual conditions were used with regard to analysis of the effects of amplitude (in)congruence, and four bimanual conditions for analysis of the effects of form (in)congruence. In addition, there were six unimanual (control) conditions, i.e., three for each hand: 1) Single large circle; 2) Single small circle; 3) Single line. In each task condition, one practice trial and three experimental trials were performed (a total of 21 experimental trials). Each trial consisted of 15 movement cycles, of which cycles 6 to 12 were used for analysis. The order of task conditions was counterbalanced across participants. For each dependent measure, the average of the experimental trials in each task condition was used for further statistical analysis. Figure 2 a and b shows an example of the movement trajectories of the affected and non-affected arm of a 10-year old boy with hemiplegic cerebral palsy in the circle-line task.

Table 2  Bimanual Conditions (unimanual control conditions not shown). Conditions in the upper left box were used for the analysis of amplitude incongruence, conditions in the lower right box for analysis of form incongruence.

<table>
<thead>
<tr>
<th>Left-limb task</th>
<th>Circle 17 cm</th>
<th>Circle 9 cm</th>
<th>Line 9 cm</th>
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</thead>
<tbody>
<tr>
<td>Circle 17 cm</td>
<td>C17 - C17</td>
<td>C17 - C9</td>
<td></td>
</tr>
<tr>
<td>Circle 9 cm</td>
<td>C9 – C17</td>
<td>C9 – C9</td>
<td>C9 – L9</td>
</tr>
<tr>
<td>Line 9 cm</td>
<td>L9 – C9</td>
<td>L9 – L9</td>
<td></td>
</tr>
</tbody>
</table>
Data Analysis

Pen trajectories were analyzed with the OASIS software package (de Jong, Hulstijn, Kosterman, & Smits-Engelsman, 1996). Pen signals were first smoothed with a 7-point median filter. The differentiated signal was then low pass filtered (Butterworth dual pass, cut-off frequency 10 Hz). Pen signals were decomposed in an X- and Y-axis component.

Data analysis focused on the temporal and spatial characteristics of the individual limb trajectories by means of cycle duration, and the ratio of the amplitude in X- and Y-axis (index of circularity). Interlimb coordination was also determined by calculating the relative phase between the affected and non-affected limb for the Y-axis only.

Figure 2a—Circle–line task. Movement trajectories of the non-affected (upper panels) and affected arm (lower panels) of participant #6 when he was asked to draw circles in the single condition (left panels) and in the bimanual incongruent condition (right panels).
Figure 2b—Circle–line task. Movement trajectories of non-affected (upper panels) and affected arm (lower panels) of participant #6 when he was asked to draw lines in the single condition (left panels) and in the bimanual incongruent condition (right panels).
Cycle Duration. Cycle duration was defined as the time elapsing between two successive peaks along the Y-axis component. Mean cycle duration was calculated for cycles 6 to 12, and the means were averaged across these cycles.

Coefficient of Variation (CV) of cycle duration (SD/Mean) was used as temporal variability measure because it takes into account differences in cycle duration across experimental conditions. Mean coefficient of variation of cycle duration was calculated for cycles 6 to 12, and the means were averaged across these cycles.

Amplitude. Amplitude of circle drawing was determined for the X-axis and Y-axis. Mean scores of amplitude-X and amplitude-Y were calculated for cycles 6 to 12, and the means were averaged across these cycles.

Circularity Index. A circularity index was calculated from the amplitude ratio-XY (amplitude X/amplitude Y) was used as a measure of circularity of the drawing movements. Mean amplitude ratio-XY were calculated for cycles 6 to 12, and the means were averaged across these cycles. Note that for drawing a perfect line the circularity index is 0, and for drawing a perfect circle the index is 1. The circularity index thus ranged from 0 (perfect line) to 1 (perfect circle). Therefore, for each trial the amplitude ratio-XY scores larger than 1 were recoded (e.g., a ratio of 1.10 was recoded to a ratio of 0.90).

Variability of Amplitude Ratio-XY was used as spatial variability measure. Mean variability of amplitude ratio-XY was calculated for cycles 6 to 12, and the means were averaged across these cycles.

Relative Phase. The relative phase between the impaired and unimpaired limb was determined for the Y-axis, because in line drawing it could not be determined for the X-axis. The continuous phase of the left ($\phi_L$) and right ($\phi_R$) hand pen signals were calculated for the Y-axis component following the algorithm used by Kelso, Scholz, and Schöner (1986). This resulted in a continuous phase signal for each arm:

$$\phi_{LY-axis} = \arctan \left( \frac{dX_{LY-axis}}{dt} / X_{LY-axis} \right)$$

and

$$\phi_{RY-axis} = \arctan \left( \frac{dX_{RY-axis}}{dt} / X_{RY-axis} \right)$$

where $X_L$ and $X_R$ are the normalized position time series, and $dX_L/dt$ and $dX_R/dt$ represent its normalized instantaneous velocity. The relative phase between left and right limb for the Y-axis was defined by

$$\phi_{LR \ Y-axis} = \phi_{RY-axis} - \phi_{LY-axis}$$

Mean relative phase ($\phi$) and the variability of the relative phase (SD$\phi$) were calculated for cycles 6 to 12 and averaged across these cycles. A large variability of the relative phase is associated with poor coordination stability.

Statistical Analysis

Significance for spatial accommodation was tested for amplitude incongruence (large/small circles) and form incongruence tasks (circles/lines) separately with a 3 [coupling condition (bimanual congruent, bimanual incongruent, single] × 2 arm (affected, non-affected) ANOVA with repeated measures for the factors coupling condition and arm. Post hoc contrasts were applied to test for significance between coupling conditions. Huynh-Feldt corrected significance levels were used for repeated measures factors in which the assumption of sphericity was violated.
Results

Amplitude Incongruence (Small/Large Circles)

Large Circles

Circularity Index. Circle drawing of the affected arm was less circular compared to the non-affected arm, $F(1,9) = 14.09, p < .01$ (Figure 3). No significant effect of coupling condition was found ($p > .10$), or significant interaction effect was found ($p > .40$).

![Figure 3—Large circle–small circle task. Circularity index for the affected and non-affected arm in the single, bimanual congruent and bimanual incongruent condition.](image)

Amplitude-X. Amplitude-X of the affected arm was smaller than that of the non-affected arm, $F(1,9) = 17.88, p < .01$ (Figure 4). A significant coupling condition × arm interaction, $F(2,8) = 6.16, p < .01$, revealed that amplitude-X of the non-affected arm was similar among conditions, whereas amplitude-X of the affected arm was smaller in the bimanual incongruent condition compared to the single condition ($p < .05$) but not in comparison to the bimanual congruent condition ($p > .20$).

Amplitude-Y. Amplitude-Y of the affected arm was significantly smaller than that of the non-affected arm, $F(1,9) = 9.24, p < .01$ (Figure 4). A significant coupling condition × arm interaction, $F(2,8) = 4.40, p < .05$, revealed that amplitude-Y of the non-affected arm was similar among conditions, whereas amplitude-Y of the affected arm was significantly smaller in the bimanual incongruent condition compared to the single condition ($p < .01$). There was a tendency that amplitude-Y of the affected arm was smaller in the bimanual incongruent compared to the bimanual congruent condition ($p = .08$).
Variability of Amplitude Ratio-XY. Variability of amplitude ratio-XY of the affected arm was larger than that of the non-affected arm, $F(1,9) = 22.33, p < .01$ ($M = 0.20$ and $M = 0.11$, respectively). No other significant effects were found.

Cycle Duration. A significant coupling condition $\times$ arm interaction, $F(2,8) = 3.59, p < .05$, showed that in the single condition cycle duration of the affected arm was longer ($M = 0.84$ s) compared to that of the non-affected arm ($M = 0.77$ s), whereas in the bimanual conditions cycle duration of both arms did not differ (bimanual congruent $M = 0.66$ s; bimanual incongruent $M = 0.78$ s).

Coefficient of Variation (CV) of Cycle Duration. A significant effect of coupling condition, $F(2,8) = 3.95, p < .05$, showed that CV of cycle duration was larger in the single compared to the bimanual incongruent condition ($p = .05$) (Figure 5). CV of cycle duration of the affected arm was significantly larger than that of the non-affected arm, $F(1,9) = 38.11, p < .001$. A significant coupling condition $\times$ arm interaction effect, $F(2,8) = 5.04, p < .05$, revealed that CV of cycle duration was reduced in the bimanual congruent and incongruent condition compared to the single condition ($p < .05$).
Amplitude Incongruence (Small/Large Circles)

Small Circles

Circularity Index. A near significant effect of coupling condition was found, $F(2,8) = 3.32, p = .06$, showing a tendency that circles were less circular (amplitude-Y > amplitude-X) in the bimanual incongruent condition. Circle drawing of the affected arm was less circular compared to the non-affected arm, $F(1,9) = 88.06, p < .001$ (Figure 3). No significant interaction effect was found ($p > .80$).

Amplitude-X. Amplitude-X of the non-affected arm was larger, $F(1,9) = 17.88 p < .01$, than that of the affected arm (Figure 4). A significant coupling condition × arm interaction, $F(2,8) = 3.74, p < .05$, revealed that amplitude-X of the non-affected arm was significantly larger in the bimanual incongruent condition compared to the single condition ($p < .05$), whereas amplitude-X of the affected arm was similar among conditions. There was a tendency that amplitude-X was larger in the bimanual incongruent condition compared to the bimanual congruent condition ($p = .09$).

Amplitude-Y. A significant effect of coupling condition, $F(2,8) = 12.33, p < .01$, showed that amplitude-Y in the bimanual incongruent condition was significantly larger compared to the bimanual congruent, and single condition ($p < .05$ and $p < .01$, respectively).

Variability of Amplitude Ratio-XY. Variability of amplitude ratio-XY of the affected arm was larger than that of the non-affected arm, $F(1,9) = 20.68, p < .01$ (M = 0.21; M = 0.12, respectively). No other significant effects were found.

Cycle Duration. No significant effects were found (bimanual congruent M = 0.63 s; bimanual incongruent M = 0.78 s; single M = 0.61 s).

Figure 5—Large circle–small circle task. Coefficient of variation of cycle duration for the affected (A) and non-affected (NA) arm in the single, bimanual congruent, and bimanual incongruent condition.
Coefficient of Variation (CV) of Cycle Duration. CV of cycle duration of the affected arm was significantly larger than that of the non-affected arm, $F(1,9) = 5.81, p < .05$. No significant effect of coupling condition was found, although there was a tendency that the CV of cycle duration was smaller in the bimanual congruent condition compared to the other conditions ($p = .08$). No significant interaction was found ($p > .50$).

Relative Phase

Relative Phase. No significant effect of coupling condition was found (bimanual congruent $M = 2.5^\circ [SD 23.0^\circ]$; bimanual incongruent $M = 3.7^\circ [SD 28.2^\circ]$).

Variability of the Relative Phase. No significant effect of coupling condition was found (bimanual congruent $M = 17.1^\circ [SD 6.0^\circ]$; bimanual incongruent $M = 17.5^\circ [SD 5.9^\circ]$), indicating that coordination stability was equal in both conditions.

Form Incongruence (Circles/Lines)

Circles

Circularity Index. A significant effect of coupling condition, $F(2,8) = 21.99, p < .001$, indicated that the ratio-XY was significantly smaller in the bimanual incongruent compared to the bimanual congruent and single condition (both, $p < .01$) (Figure 6). Circularity of drawing movements of the affected arm was significantly smaller compared to that of the non-affected arm, $F(1,9) = 44.31, p < .001$). No significant interaction was found ($p > .50$).

![Figure 6—Circle–line task. Circularity for the affected and non-affected arm in the single, bimanual congruent, and bimanual incongruent condition.](image-url)
Variability Amplitude Ratio-XY. The variability of the amplitude ratio-XY of the affected arm was larger compared to that of the non-affected arm, $F(1,9) = 26.51, p < .001$ (M = 0.20, M = 0.12, respectively). No other significant effects were found ($p > .10$).

Cycle Duration. A significant effect of coupling condition, $F(2,8) = 5.88, p < .01$, indicated that cycle duration was significantly longer in the bimanual incongruent compared to the bimanual congruent and single condition ($p < .05$, and $p < .01$, respectively) (bimanual congruent M = 0.66 s; bimanual incongruent M = 0.78 s; single M = 0.62 s). Cycle duration of drawing movements of the affected arm was significantly longer compared to that of the non-affected arm, $F(1,9) = 7.37, p < .05$ (M = 0.72, M = 0.65, respectively).

Coefficient of Variation (CV) of Cycle Duration. A significant effect of coupling condition, $F(2,8) = 5.86, p < .05$, revealed that CV of cycle duration was smaller in the bimanual congruent condition compared to the bimanual incongruent and single condition ($p < .01$, and $p < .05$, respectively) (Figure 7). A significant effect of arm, $F(1,9) = 18.51, p < .01$, indicated that CV of cycle duration for the affected arm was larger than that of the non-affected arm. No significant interaction was found ($p > .20$).

![Figure 7](image_url)

Figure 7—Circle–line task. Coefficient of variation of cycle duration for the affected (A) and non-affected (NA) arm in the single, bimanual congruent, and bimanual incongruent condition.

Lines

Circularity Index. A significant effect of coupling condition was found, $F(2,8) = 14.56, p < .001$, indicating that the circularity index was significantly smaller in the bimanual incongruent compared to the bimanual congruent and single condition (both, $p < .01$). The circularity index of drawing movements of the affected arm was significantly larger compared to that of the non-affected arm, $F(1,9) = 4.95, p < .01$. 


Variability Amplitude Ratio-XY. A significant effect of coupling condition, $F(2,8) = 17.68, p < .001$, showed that the variability of the amplitude ratio-XY was significantly larger in the bimanual incongruent compared to the bimanual congruent and single condition (both, $p < .01$). The variability of the amplitude ratio-XY of the affected arm was larger compared to the ratio-XY of the non-affected arm, $F(1,9) = 11.84, p < .01$ ($M = 0.09$, $M = 0.05$, respectively). No significant interaction was found ($p > .80$).

Cycle Duration. A significant main effect of coupling condition, $F(2,8) = 5.88, p < .01$, showed that cycle duration was significantly longer in the bimanual incongruent compared to the bimanual congruent and single condition (contrast analysis $p < .05$, and $p < .01$, respectively) (bimanual congruent $M = 0.64$ s; bimanual incongruent $M = 0.78$ s; single $M = 0.61$ s). A significant coupling condition $\times$ arm interaction, $F(1,9) = 6.86, p < .01$, indicated that cycle duration of the non-affected arm was longer in the single condition ($M = 0.55$ s), but shorter in the bimanual incongruent condition ($M = 0.72$ s), whereas cycle duration of the affected arm was comparable among the two conditions.

Coefficient of Variation (CV) of Cycle Duration. A significant effect of coupling condition, $F(2,8) = 11.89, p < .01$, indicated that CV of cycle duration was larger in the bimanual incongruent condition compared to the bimanual congruent and single condition (both, $p < .01$) (Figure 7). A significant coupling condition $\times$ arm interaction, $F(2,8) = 7.26, p < .01$, revealed that the CV of cycle duration in the non-affected arm in the bimanual incongruent condition was much larger compared to the bimanual congruent and single condition, whereas this was not the case for the affected arm.

Relative Phase

Relative Phase. No significant effect was found of coupling condition (bimanual congruent $M = 0.4^\circ$ [SD 15.4°]; bimanual incongruent $M = –4.8^\circ$ [SD 18.0°]).

Variability of the Relative Phase. The variability of the relative phase was significantly larger, $F(1,9) = 8.83, p < .05$, in the bimanual incongruent condition ($M = 19.7^\circ$ [SD 7.9°]) compared to the bimanual congruent condition ($M = 14.5^\circ$ [SD 3.9°]), indicating that bimanual coordination was less stable in the form incongruent condition.

Discussion

The aim of the present study was to investigate spatial coupling of the affected and non-affected arm of children with hemiplegic cerebral palsy in bimanual rhythmic drawing tasks with different amplitudes and different form. The question was whether amplitude or form incongruence resulted in accommodation of the affected or non-affected arm or both, and whether amplitude or form incongruence resulted in an increase of temporal variability of the affected and non-affected arm, and in a decrease of coordination stability.

Accommodation of Affected and Non-Affected Arm

The main finding of the present study is that for the amplitude and form incongruence manipulation we found different accommodation effects with respect to whether the affected or non-affected arm accommodated or both. For form incongru-
ence, accommodation of both the affected and non-affected arm (about equivalent in magnitude) was found (Figure 6). Circles became less circular, and lines became less linear and more ellipsoid. Neither the affected nor the non-affected arm dominated in the coupling. These findings are in agreement with previous studies on spatial coupling using the same circle-line task, and demonstrate that children with hemiplegic cerebral palsy did not respond very differently in comparison to non-disabled participants, except that drawing a circle or line with the affected arm was less perfect and spatially more variable (Franz et al., 1991; Franz, 1997). Since, as we stated before, spatial interference due to differences in form have been associated with the level of movement planning, this finding suggests that aspects of planning in bimanual coordination are being preserved in children with (mild) hemiplegic cerebral palsy.

For amplitude incongruence, findings were different. When drawing small circles in the incongruent condition was required, the non-affected arm accommodated its amplitude in the X- and Y-plane, whereas the affected arm did not change its amplitude in the X-plane (Figure 4). When drawing large circles in the incongruent condition was required, the non-affected arm did not change its amplitude in the X- or Y-plane, whereas the affected arm accommodated its amplitude in the X- and Y-plane compared to single-handed performance. Figure 4, however, shows that accommodation also occurred in the bimanual congruent compared to the single-hand condition. The most likely explanation for this finding is that involvement of postural movements did occur during drawing large circles with the affected arm in the single condition, probably as a compensation strategy for interjoint coordination problems or limitation in the range of reach (see also Steenbergen et al., 2000). Postural movements as compensation strategy to reach the 17 cm amplitude of the large circle cannot be used in bimanual symmetric circle drawing in the X-plane because the hands move towards the longitudinal axis. Despite this possible compensation a tendency for accommodation of amplitude of the affected arm in the Y-plane in the bimanual incongruent condition was still found in comparison with the bimanual congruent condition. In short, results showed that for large circles the non-affected arm dominated the coupling (it did not change its amplitude) whereas the affected arm tended to accommodate in the Y-plane. This finding is in accordance with findings in non-disabled participants in which the dominant hand dominated the spatial coupling (Sherwood, 1994b). For small circles, the affected arm dominated the coupling (it did not change its amplitude in the X-plane) and the non-affected arm accommodated. These findings are more in line with studies on temporal coupling in hemiplegic children during bimanual goal-directed movements (Steenbergen et al., 1996; 2000). What these findings also show is that whether the affected or non-affected arm accommodates also depends on task-specific constraints (cf. Utley & Sugden, 1998).

Temporal Variability and Bimanual Coordination Stability

Spatial incongruence in bimanual coordination clearly resulted in an increase of temporal variability of the affected and non-affected arm and in a decrease of bimanual coordination stability. As was hypothesized, this was more evident in the form incongruence task than in the amplitude incongruence task (see Figure 5 and 7). In accordance with this finding, bimanual coordination stability was only significantly decreased for form incongruence, but not for amplitude incongruence.
In a similar vein, spatial variability was significantly increased for form incongruence, but not for amplitude incongruence.

An increase of temporal variability of affected and non-affected arm in the incongruent condition was observed despite the fact that accommodation of the affected or non-affected arm occurred. This was due to the fact that generally the spatial trajectories of the affected and non-affected arm still did not resemble each other very much after accommodation, and, hence, simultaneous activation of homologous muscles was not optimal. This was certainly the case for the small circle task (Figure 6) in which the largest increase of temporal variability was observed in the incongruent condition compared to single-handed performance (Figure 7). In the large circle-small circle task, a somewhat different picture emerges. It appeared that in one combination in the incongruent condition (i.e., the affected arm is required to draw a large circle and the non-affected arm a small circle) the circularity index (see Figure 3), and the amplitudes X and Y (Figure 4), of the affected and non-affected arm start to resemble each other, resulting in a decrease of the temporal variability of the affected arm (see Figure 5, circles 17 cm/A-arm) and an increase of the temporal variability of the non-affected arm compared to single-handed performance (Figure 5, circles 9 cm/NA-arm). This finding is in agreement with the study of Volman et al. (2002b). For the other combination in the incongruent condition (i.e., the non-affected arm is required to draw a large circle and the affected arm a small circle), the circularity index, and the amplitude-X and -Y, of the affected and non-affected arm were still rather different in spite of the accommodation (particularly of the affected arm) that occurred, resulting only in small changes of the temporal variability compared to the single-handed condition (Figure 5, NA-arm circles 17 cm/NA-arm and circles 9 cm/A-arm). Altogether, these findings show that the degree of accommodation does influence the level of the temporal variability of the individual arms.

**Spatial Coupling by Interhemispheric Transfer**

Research on spatial coupling in patients that underwent callosotomy have provided evidence that the posterior callosum mediates the transfer of spatial information (i.e., aspects of movement planning) during bimanual coordination (Eliasson, Baynes, & Gazzaniga, 1999; Franz, Eliasson, Ivry, & Gazzaniga, 1996). Furthermore, it has been suggested that the parietal cortex (parieto-premotor areas) is the likely locus from where interference arises when directionally incompatible movements are performed (Eliasson et al., 1999; Wenderoth, Debaere, Sunaert et al., 2004). The finding of the present study that hemiplegic children show accommodation of both affected and non-affected arm in the circle-line task suggests that interhemispheric transfer of spatial information does occur. This implies that there is, at least to some extent, cortical activation in the hemisphere contralateral to the affected arm. In fact, most children in the present study showed a rather mild hand motor impairment. Particularly for this group of hemiplegic children it was found in studies that investigated hand motor reorganization using neuro-imaging that although (ipsilateral) reorganization in the unaffected hemisphere had occurred, crossed cortico-spinal projections to the affected hand were preserved (Carr, Harrison, Evans, & Stephens, 1993; Staudt, Grodd, Gerloff et al., 2002). In more severely affected children with cerebral palsy the latter was not the case. This is probably
why in the present study hemiplegic children did not respond very differently in the circle-line task compared to non-disabled participants (Franz, 1997).

**Implications for Practice**

A salient question in the treatment of children with hemiplegic cerebral palsy is how the function of the affected arm can be enhanced both for unimanual and bimanual functional activities. Recent studies have suggested improvement in the movement of the affected arm in patients with hemiplegia after stroke during and following bilateral training (Cunningham, Phillips Stoykov, & Walter, 2002; Mudie & Matyas, 2000), and in children with hemiplegic cerebral palsy during symmetric bimanual circle drawing (Volman et al., 2002b). Findings in the present study for the bimanual spatial congruent tasks are in line with the aforementioned studies. An important question, however, is whether bilateral symmetric training will result in transfer to functional bimanual activities requiring both hands to act in a temporally or spatially different manner. The latter has to be doubted since the present study shows that even in a relatively simple two-dimensional drawing task, amplitude and especially form incongruence in bimanual coupling leads to an increase of temporal variability of the affected and non-affected arm, and in a decrease of coordination stability (increase of variability of the relative phase). As a result, bimanual task performance will be less predictable. It is still under debate whether improvement of motor function in children with cerebral palsy should focus on basic movement patterns or on functional tasks. A functional approach seems promising (e.g., Ketelaar et al., 2002). Improvement of functional bimanual tasks in hemiplegic children, one might argue, should therefore focus on the bimanual functional task itself as a starting point, even at the cost of decreased coordination stability and increased temporal variability. A recent study with non-disabled participants has shown that spatial interference in bimanual coordination tasks with spatially different demands for left and right hand can be reduced by bimanual training of the task as a whole (Wenderoth et al., 2004). It would be interesting to investigate whether hemiplegic children also have the capacity to reduce spatial interference effects.

**Conclusion**

Amplitude incongruence in bimanual coordination resulted in accommodation of the affected arm (large circles required) or non-affected arm (small circles required) of hemiplegic children with cerebral palsy. Form incongruence resulted in accommodation of both affected and non-affected arm similar to that found in non-disabled participants. The latter finding suggests that aspects of planning in bimanual coordination of hemiplegic cerebral palsy were not affected. Despite this accommodation, form incongruence in bimanual coordination resulted in an increase of temporal variability of the affected and non-affected arm, and a decrease of coordination stability. For amplitude incongruence, accommodation in one combination resulted in close resemblance of spatial trajectories, and, hence, in a decrease of temporal variability of the affected arm. The conclusions of the present study must be viewed with caution since the number of participants in the present study was rather limited. Furthermore, these findings cannot be generalized to hemiplegic children with more severe hand motor impairments.
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References


