RESEARCH ARTICLE

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Bimanual movement coordination in spastic hemiparesis

Received: 4 May 1995 / Accepted: 16 December 1995

Abstract A Fitts' task was used to examine whether the large movement asymmetry in subjects with spastic hemiparesis can be reduced or eliminated when both limbs are required to perform functionally equivalent tasks. Furthermore, it was determined whether any such benefit was expressed as mutual accommodation, or whether one hand "slaves" the other. Finally, the effect of increased task constraints on the magnitude of the asymmetry was considered. A group of ten students served as controls. Subjects had to grasp small balls and subsequently place them into holes. As expected, large total response time differences were present between the hands of the hemiparetic subjects in the unimanual conditions. However, 92% of the difference between hands was eliminated in the bimanual conditions. It is argued that the observed temporal invariance, or time locking, between hands in the bimanual conditions might be facilitated through the activity of bilateral controls exerted from each hemisphere and neural crosstalk at different levels of the central nervous system. Still, an asymmetric tendency remained in the bimanual conditions: a tendency existed for the impaired hand to reach the "target" later in time compared with the dominant hand. This tendency was enlarged as the asymmetry in task demands for the two limbs increased.

Key words Human movement · Spastic hemiparesis · Bimanual coordination

Introduction

In individuals suffering from spastic hemiparesis, the performance characteristics of reaching and grasping movements made by the impaired limb differ markedly

from those of the unimpaired limb. Trombly (1992), examining five subjects with left hemiparesis, observed that movements of the impaired arm were less continuous and exhibited proportionately longer deceleration phases than those of the unimpaired arm. Brown et al. (1989) and Fisk and Goodale (1988) have shown that movements of the unimpaired hand of subjects suffering from hemiparesis are slower than movements made by the dominant hand of non-patients. However, while most daily activities involve the cooperative interaction of the two hands, remarkably little attention has been devoted to bimanual coordination in individuals with hemiparesis (Jung and Dietz 1975; Sugden and Utley 1995). These activities form the focus of the present investigation.

Investigations conducted with healthy subjects have suggested that, in bimanual movements, the central nervous system acts to constrain the muscles of the upper limbs in functional task-specific groupings or "coordinative structures" (Kelso et al. 1979a,b, 1983). Kelso and coworkers used a Fitts' task (Fitts 1954) to examine the timing of unimanual and bimanual reaching movements to separate targets. The results for one-handed reaching were in line with predictions stemming from Fitts' Law. The movement times (MT) obtained satisfied the relationship $MT = a + b \log_2 (2A/W)$, where a and b are constants, A is movement distance and W is target width.

By extension, it would be predicted that, for bimanual reaching movements to targets which differed in terms of their Index of Difficulty [$ID; \log_2 (2A/W)$], the hand moving to the easy target would reach the target before the hand moving to the difficult target. However, the results obtained by Kelso et al. demonstrated that both hands reached the targets at virtually the same time. These data were interpreted as indicating a coordinative structure type of control whereby the two limbs were "constrained to function as a single synergistic unit within which component elements vary in a related manner" (Kelso et al. 1983, p. 369). It has been shown subsequently that absolute synchrony is not obtained in circumstances in which the asymmetry in task demands (target size, movement amplitude or hurdle height) is in-

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creased (e.g. Goodman et al. 1983; Marteniuk et al. 1984; Fowler et al. 1991).

The primary aim of the present experiment was to examine bimanual coordination in subjects suffering from spastic hemiparesis. Specifically, we sought to determine whether performance asymmetries are decreased or eliminated when the two hands are required to perform functionally equivalent tasks. We refer to this construct as bimanual facilitation. Consideration was also given to the issue of whether such facilitation is predicated upon mutual accommodation, whereby the duration of the bimanual response is intermediate between that of the hands in the unimanual conditions, or upon unidirectional accommodation, whereby the duration of the bimanual response is determined primarily by the unimanual response time of the impaired hand.

We also examined the influence of increased task demands upon the coupling of the hands. We refer to this construct as bimanual coupling. To address these questions, a reach-grasp-placement task, closely resembling the paradigm employed by Kelso et al. (1979a,b, 1983) was used; subjects were required to pick up a small ball (12 mm in diameter) and place it into a hole as quickly as possible.

Subjects and methods

Subjects

The experiment was performed on two groups of subjects. First, a group of normal healthy university students ($n=10$; mean age 21 years 8 months, SD 1 year 2 months) was used, not as a control

group per se but to check whether the present task produced (more or less) similar results to those of Kelso et al. (1979a,b, 1983). Secondly, a hemiparetic group was used that consisted of 14 children (mean age 18 years 0 months, SD 1 year 5 months) of which six suffered from spastic hemiparesis on the left side and eight suffered from spastic hemiparesis on the right side. All subjects participated on a voluntary basis, and gave signed consent prior to the start of the experiment. All subjects in the student group had normal or corrected-to-normal vision. One subject in the hemiparetic group suffered from impaired vision of the left eye (no. 12, see Table 1). No subject in this group exhibited hemineglect.

Subject profile (experimental group)

The experiment was carried out at a special institute in The Netherlands, called Werkenrode. At this institute, physically disabled children between 12 and 20 years of age from all parts of the country can receive special education. To be enrolled into this special education program a certain degree of manual ability is needed among other factors such as endurance and intelligence.

The dexterity of each child is assessed in the occupational therapy department by means of the Manual Abilities Scanning Test (MAST: Wilcock 1982). An average score of at least 33% is needed for acceptance into the special education program. Initial selection of subjects for the present experiment was based on their scores on this dexterity test; only subjects with average scores exceeding 33% were selected (Table 1). In addition, prior to the experiment subjects were screened with respect to the residual motor abilities of the paretic limb. Subjects were asked to pick up a small ball 12 mm in diameter, equivalent to that used in the experiment. If, due to severe spasticity and/or lack of manual dexterity, this was not reliably accomplished, he or she was excluded from further experimentation. On the basis of these exclusion criteria, three subjects were not used for further testing. It was generally observed that, as a result of spasticity, balls were grasped using a power grip in which the thumb remained in an adducted position, the fingers were overextended and the wrist flexed [see Twitchell (1958) for a description of reaching and grasping problems in children with cerebral palsy].

Table 1 Overview of relevant subject information

Subject	Age (years)	Diagnosis	Aetiology	MAST score	Sex	Other
1	16.0	Left spastic hemiparesis	Lack of oxygen during birth	44.5	M	Aphasia
2	17.6	Left spastic hemiparesis	Lack of oxygen during birth	37.6	M	-
3	20.2	Left spastic hemiparesis	Contusio cerebri (accident at age 15 years)	64.3	M	-
4	19.2	Left spastic hemiparesis	Cerebral vascular accident at age 16 years	53.8	M	-
5	18.3	Left spastic hemiparesis	Lack of oxygen during birth	38.3	M	-
6	19.4	Left spastic hemiparesis	Lack of oxygen during birth	33.9	M	-
7	16.6	Right spastic hemiparesis	Removal of brain tumour in cerebellum (age 7 and 10 years)	49.1	M	-
8	18.3	Right spastic hemiparesis	Lack of oxygen during birth	51.2	M	-
9	18.1	Right spastic hemiparesis	Lack of oxygen during birth	74.6	M	Epileptic
10	18.0	Right spastic hemiparesis	Cerebral vascular accident at age 7 years	34.2	M	Horner syndrome
11	18.9	Right spastic hemiparesis	Lack of oxygen during birth	46.7	M	Corrected vision
12	20.1	Right spastic hemiparesis	Lack of oxygen during birth	61.2	M	Left eye 10% vision
13	15.3	Right spastic hemiparesis	Viral meningitis at age 2 years	35.6	M	Dysarthria
14	16.1	Right spastic hemiparesis	Contusio cerebri (accident at age 2 years)	42.1	M	Epileptic

Fig. 1 The experimental set-up (top view)

Clinical diagnosis of the experimental group was based on neurological examinations, surgical records, electroencephalograms (EEGs) and CT scans conducted at a number of hospitals and rehabilitation centres throughout the country. All subjects had established spasticity and had received extensive rehabilitation programs. The causes of the spastic hemiparesis were various (Table 1).

For four of the six subjects with spastic hemiparesis on the left side the aetiology was congenital, arising as a consequence of lack of oxygen at birth. The other two subjects acquired cerebral damage at a later age: one had a cerebral vascular accident at the age of 16 years and the other suffered from contusio cerebri as a result of a traffic accident at the age of 15 years.

For four of the eight subjects suffering from right spastic hemiparesis the aetiology was congenital. Of the other four subjects with acquired cerebral damage, one had suffered from a cerebral vascular accident on the age of 7 years. In one subject, after neurological examination and EEG, a tumour was discovered in the cerebellum and removed at the age of 7 and later at the age of 10 years. Cerebral damage afterwards was assessed and confirmed by CT scan. The third subject had suffered viral meningitis at the age of 2 years, and the final case was one of contusio cerebri caused by an accident at the age of 2 years.

Apparatus

The experimental task was a slightly modified version of one of the subtests of MAST. The experimental setup is displayed schematically in Fig. 1. Two boxes (12.5 cm × 12.5 cm) were placed on the top of a desk. A contact switch was inserted under the lid of these boxes. When the hand rested on the lid of the box the switch remained in a closed position. Once the hand started to move the switch was released, providing a consistent measure of the start of the movement.

The MAST apparatus was placed 15.0 cm in front of these boxes. Two grooves were present in which small balls (12 mm in diameter) were placed. These grooves had a slight inclination such that the balls, once released, always rolled towards the subject. The distance between the ball and the middle of the reaction-time boxes was 21.5 cm. A panel with two holes could be placed on the apparatus such that the middle of each hole was 8.7 cm in front of and 16.0 cm on the medial side of the closest ball (Fig. 1). A microphone, which registered the sound of the falling ball, was mounted underneath each hole. Both the contact switches and the microphones were interfaced with a personal computer (Tandon, 486/33 MHz). At the start of each trial a high-frequency GO signal (1000 Hz; duration 100 ms) was generated by the computer. Simultaneously, the computer started registering the time of all events.

Task and experimental procedure

The subject was seated comfortably on a chair with armrests. To establish a stable position, the height of the chair was changed so that the subject's feet were flat on the ground. In some cases a foot bench was used. The height of the table could also be varied and was installed so that the forearm of the subject was parallel with the ground when it was placed on the table top. Before the start of the experiment this installation was carried out very carefully, to obviate the possibility that insuitable seating could lead to fatigue or exacerbate and aggravate spasticity (cf Barnes et al. 1994).

Instructions

Written, as well as spoken instructions were given prior to the experiment. Subjects were required to pick up the small ball and place it into the nearest hole as quickly as possible following the computer-generated GO signal. In the bimanual conditions subjects were instructed to place both balls into the designated holes. However, no explicit instruction was given to move both arms in synchrony.

At the start of each trial the experimenter gave a warning signal. After this warning signal the GO signal was generated at random within a 2-s interval. A trial was completed when the ball(s) was (were) placed in the hole(s). Following each trial, subjects were required to place their hand(s) back on the contact boxes. When both contacts were closed the experimenter gave a warning signal signifying the start of the next trial. On each trial two measures were calculated for each hand: reaction time (time from GO signal to hand lift) and total response time (time from GO signal to ball release).

Design

Each subject performed a block of trials in each of eight experimental conditions. In four unimanual conditions, the dominant or non-dominant hand moved in isolation to either the 13-mm or 44-mm hole. In four bimanual conditions the hole sizes were either equal (i.e. 13 mm or 44 mm) or unequal (i.e. 13 mm for the dominant hand and 44 mm for the non-dominant hand, or vice versa).

In coding trials the hole size for the dominant hand (i.e. the non-impaired hand for the subjects with spastic hemiparesis) is always given prior to that for the non-dominant hand (i.e. the impaired hand for the subjects with spastic hemiparesis). For example, 44-0 signifies a unimanual movement performed with the dominant hand to the large hole, 13-44 indicates a bimanual movement, with the dominant hand moving to the small (13-mm) hole and the non-dominant hand moving to the large (44-mm) hole. A total of 12 trials were performed in each experimental condition. The first two trials in each condition were familiarization trials which were not used for analysis.

The ordering of experimental conditions for each subject was determined on the basis of an incomplete counterbalanced between-subjects design. The experiment took approximately 45 min to complete.

Data analysis

Reaction-time data were analysed using a two within [Context (unimanual vs bimanual) and Hand (dominant vs non-dominant)] repeated measures analysis of variance design.¹

¹ Hole size was omitted as a factor in this analysis, for it was not expected that this variable would influence reaction time. This suggestion was based on the type of task used: Roughly, the task can be divided into two subtasks: first, grasping the ball(s) and, second, placing the ball(s) into the designated holes. As such the length of the reaction time is critically dependent upon the constraints imposed in the first subtask. Since the ball size was invariant across all trials the only variables of interest for reaction time were the effect of Hand and Context.

Response-time data were analysed using two separate repeated measures analysis of variance designs.

In the first analysis ("bimanual facilitation"), the unimanual conditions 44-0, 13-0, 0-44 and 0-13 were compared with the corresponding bimanual equal-hole-size conditions 44-44 and 13-13. The resulting design included the following factors: (1) Context (unimanual vs bimanual, equal hole size), (2) Hole (44 mm vs 13 mm), (3) Hand (dominant vs non-dominant).

In the second analysis ("bimanual coupling"), the bimanual equal-hole-size conditions 44-44 and 13-13 were compared with the bimanual unequal-hole-size conditions 44-13 and 13-44. This resulted in a design with the following factors: (1) Context (bimanual equal hole size vs bimanual unequal hole size); (2) Hole (44 mm vs 13mm); (3) Hand (dominant vs non-dominant).

Analyses were performed separately for each subject group. In the hemiparetic group, the side of the spastic hemiparesis was included as an additional between-subject factor in the analysis of variance design. Post-hoc tests were performed using Newmann-Keuls analysis, with $P < 0.05$ significance level. Since the primary aim of the present experiment was to examine bimanual coordination in subjects suffering from spastic hemiparesis, we also calculated the within-subject correlations of the dependent variables between the impaired hand and the unimpaired hand for each bimanual condition.

Results

The results are presented in two parts. The results from the student group are presented first and compared with those of Kelso et al. (1979a,b, 1983). The results obtained from the hemiparetic group are then presented.

Student group ($n=10$)

Reaction time

Mean reaction times and the corresponding standard deviations for the student group are shown in Table 2. There were no effects attributable to hand. These data indicate that in the bimanual conditions movements of the dominant and non-dominant hand were initiated simultaneously. These results thus concur with those obtained by Kelso et al. (1979a,b, 1983), and point to a common source of activation for both limbs at the start of the movement. It was also evident that moving with two hands prolonged reaction time compared with the unimanual conditions [278 ms vs 256 ms; $F(1,9)=8.05$, $P < 0.05$].

Table 2 Mean reaction times (and standard deviations), in milliseconds, for the student group in the unimanual and bimanual conditions

Condition	Students ($n=10$)	
	Dominant hand	Non-Dominant hand
Unimanual	255 (22)	257 (34)
Bimanual	281 (32)	275 (36)

Fig. 2 Total response times (ms) and standard deviations for the student group ($n=10$) in all movement conditions. The first two sets of double bars represent the unimanual (one-handed) conditions (to the large and the small hole respectively), the third and the fourth set represent the bimanual (two-handed) equal-hole-size conditions and the final two sets of bars represent the bimanual unequal-hole-size conditions. For all six sets of bars, the first displays the total response time of the dominant hand, and the second displays the total response time of the non-dominant hand

Total response time

Analysis 1: Bimanual facilitation. The total response times and standard deviations for the student group are displayed in Fig. 2. Movements performed in the bimanual conditions were slower than those performed in unimanual conditions [$F(1,9)=23.05$, $P < 0.01$]. Movements made by the dominant hand were faster than those made by the non-dominant hand [$F(1,9)=16.56$, $P < 0.01$]. Post-hoc analysis showed that the time difference between the dominant and non-dominant hand was restricted to the unimanual conditions [$F(1,9)=11.18$, $P < 0.01$]. In the bimanual conditions both hands reached the target holes at essentially the same time, whereas in the unimanual conditions the advantage in favour of the dominant hand was on average 90 ms.

Consistent with the predictions of Fitts' Law, movements to the small hole were, on average, of 139 ms greater duration than those to the large hole [1380 ms vs 1241 ms; $F(1,9)=67.78$, $P < 0.001$]. Post-hoc analysis indicated that this effect was present in both unimanual and bimanual (equal-hole-size) conditions [$F(1,9)=6.92$, $P < 0.05$].

Analysis 2: Bimanual coupling. It was evident that both hands reached the holes at similar times in all four bimanual conditions. There was no effect of Hand nor a Hand $\times$ Context interaction. In contrast, the effect of Hole [$F(1,9)=79.13$, $P < 0.001$] and the Context $\times$ Hole interaction [$F(1,9)=34.93$, $P < 0.001$] were of statistical significance. Post-hoc analysis showed that, in conditions in which the two target holes were of equal size, movements to the large holes were completed more rapidly than movements to small holes (1324 ms vs 1502 ms).

There were no reliable differences between conditions in which the target holes were of unequal size. Post-hoc comparisons revealed that movements to the large hole were significantly slower in the unequal-hole-size conditions than in the equal-hole-size conditions (unequal hole size, 1435 ms; equal hole size, 1324 ms). On the other hand, movements directed to the small hole in the equal-hole-size conditions, were not appreciably faster than those made to the small hole in the unequal-hole-size conditions (unequal hole size, 1467 ms; equal hole size, 1502 ms).

Discussion

In the bimanual conditions, movements of the dominant and non-dominant hands were not reliably different from each other, in terms of either reaction time or response time. Even in circumstances in which the task demands for each hand differed, targets were acquired at virtually the same time. These data suggest that there exists a tight coupling between the hands. The pattern of results obtained in the unequal-hole-size conditions indicates that in these circumstances Fitts' Law may be violated. The data are thus consistent with those reported by Kelso et al. (1979a,b, 1983).

Hemiparetic group ($n=14$)

Reaction time

The mean reaction times and corresponding standard deviations for the spastic hemiparesis group are shown in Table 3. Subjects suffering from spastic hemiparesis on the left side initiated movements significantly faster than subjects suffering from spastic hemiparesis on the right side [average difference 78 ms; $F(1,12)=4.97$, $P<0.05$].

As expected, movements of the impaired hand took longer to initiate than those of the non-impaired hand [$F(1,12)=8.92$, $P<0.05$]. However, post-hoc analysis showed that differences in reaction time between the impaired and non-impaired hands were restricted to the unimanual conditions, in which the mean difference was 72 ms [$F(1,12)=5.53$, $P<0.05$]. In the bimanual conditions, the difference in reaction time between the hands was 11 ms, which was not significant. As can be seen in Table 3, it appeared that the extent to which the advan-

tage in favour of the unimpaired hand was reduced in the bimanual conditions, was greater for the right spastic hemiparesis group (unimanual, 92 ms; bimanual, 9 ms; 90% reduction) than for the left hemiparesis group (unimanual, 21 ms; bimanual, 14 ms; 33% reduction). However, the corresponding three-way interaction $\text{Hand} \times \text{Context} \times \text{Group}$ failed to reach conventional levels of statistical significance [$F(1,12)=3.78$, $P=0.08$].

In the bimanual conditions, the within-subject correlations between the impaired and the non-impaired hand ranged from 0.74 to 0.99 (median 0.95). With the exception of one subject in one condition these correlations were statistically significant. These data provide further indications of a tight coupling between the hands in the bimanual conditions.

It was also evident that movements of the non-impaired hand were initiated more slowly in the bimanual conditions (376 ms) than in the unimanual conditions (320 ms), whereas reaction times for the impaired hand were equivalent in the unimanual (382 ms) and bimanual conditions (387 ms). Overall, moving with both hands together resulted in a lengthening of the reaction times compared with moving with one hand [$F(1,12)=5.47$, $P<0.05$].

Total response time

Analysis 1: Bimanual facilitation. In contrast to the reaction-time data, there were no differences between the right and left hemiparetic groups in terms of total response time. Therefore, the total response times for both groups have been combined. These data are shown in Fig. 3.

Movements of the impaired hand were slower than those of the non-impaired hand [3087 ms vs 2143 ms; $F(1,12)=16.03$, $P<0.01$]. In addition, moving both hands together required more time than moving one hand alone [$F(1,12)=20.89$, $P<0.001$]. Post-hoc analysis showed that the differences in response time between the hands were confined to the unimanual conditions. Indeed, when moving both hands together, the difference in response time between the impaired and non-impaired hands was approximately 8% of that present when the hands were moved independently [unimanual and bimanual differences amounting to 1755 ms and 133 ms, respectively; $F(1,12)=17.94$, $P<0.05$].

Table 3 Mean reaction times (and standard deviations), in milliseconds, for the spastic hemiparesis group in the unimanual and bimanual conditions. A distinction is made between subjects suf-

fering from spastic hemiparesis on the left side and subjects suffering from spastic hemiparesis on the right side

Condition	Hemiparesis left side ($n=6$)		Hemiparesis right side ($n=8$)	
	Non-impaired hand	Impaired hand	Non-impaired hand	Impaired hand
Unimanual	291 (60)	312 (30)	341 (60)	433 (145)
Bimanual	335 (54)	349 (65)	407 (44)	416 (57)

Fig. 3 Total response times (ms) and standard deviations for the spastic hemiparesis group ($n=14$) in all movement conditions. The first two sets of double bars represent the unimanual (one-handed) conditions (to the large and the small hole respectively), the third and the fourth set represent the bimanual (two-handed) equal-hole-size conditions and the final two sets of bars represent the bimanual unequal-hole-size conditions. For all six sets of bars, the first displays the total response time of the non-impaired hand, and the second displays the total response time of the impaired hand

In the bimanual conditions, the within-subject correlations between the impaired and the non-impaired hand ranged from 0.42 to 0.99 (median 0.86). With the exception of one subject, in the 13-13 condition, these correlations were statistically significant. These data provide further indications of a tight coupling between the hands in the bimanual conditions in which the hands moved to equal-sized targets.

It was apparent that movements of the non-impaired hand were of longer duration in the bimanual conditions (2829 ms) than in the unimanual conditions (1417 ms). In contrast, movement times for the impaired hand were not reliably different in the unimanual (3172 ms) and bimanual conditions (3002 ms).

Finally, response times for movements to small target holes were greater than those to large target holes [$F(1,12)=15.40$, $P<0.01$]. In addition, post-hoc analysis of the statistically significant Hand $\times$ Hole interaction [$F(1,12)=20.16$, $P<0.001$] showed that the effect of hole-size was confined to movements of the impaired hand. For this hand smaller holes led to a lengthening of the total response times (2805 ms vs 3370 ms), whereas for the non-impaired hand the corresponding difference was not statistically reliable (2006 ms vs 2280 ms).

Analysis 2: Bimanual coupling. The preceding analysis showed that while the hands are strongly coupled in conditions in which they both move to targets of equal size, an increase in the task demands, viz. decreasing the size of the target hole, has a greater impact upon movements of the non-dominant hand. The current analysis was conducted to determine the extent to which simultaneous response execution is maintained when the hands have to move to perform tasks which are not of equal difficulty.

In particular, it was of interest to determine the consequences of increasing the difficulty of the task for the impaired hand.

When moving both hands together to targets of unequal size, the difference in response time between the impaired and non-impaired hands (152 ms) was approximately 9% of that present when the hands were moved independently (1755 ms). These data correspond closely to those obtained when the hands moved to targets of equal size (see above).

Although there was a trend for movements of the non-impaired hand to be completed, on average 152 ms, in advance of those of the impaired hand, this effect was not statistically reliable [$F(1,12)=3.98$, $P=0.07$]. There was also no indication of a Hand $\times$ Context interaction. Within-subject correlations between the two hands further supported the conclusion that movements of the impaired and non-impaired limbs were highly synchronous. Correlations ranged from 0.42 to 0.99 (median 0.88) and were in almost every case statistically significant.

However, it remained apparent that when bimanual movements were directed to targets of unequal size, there was a tendency for the non-impaired hand to reach the target somewhat in advance of the impaired hand. The failure to reach conventional levels of statistical significance may be due to the large standard deviations associated with the total response times in these conditions (Fig. 3).

Further inspection revealed that when bimanual movements were directed to targets of unequal size, the largest advantage in favour of the non-impaired hand (213 ms) was present in the 44-13 condition (Fig. 3, final set of bars). In this condition, the impaired hand was required to move to the smaller target. These data suggest that increasing task demands, by decreasing the size of the target hole size, has a larger impact on the impaired hand than on the non-impaired hand. Corroboration is provided by the presence of a statistically significant effect of Hole [$F(1,12)=16.67$, $P<0.01$] and interaction of Hand $\times$ Hole [$F(1,12)=6.01$, $P<0.05$]. Post-hoc analysis showed that the total response times of the impaired (2963 ms) and non-impaired (2945 ms) hands were equivalent for movements to large targets. However, for movements to small targets, the response duration of the impaired hand (3332 ms) was greater than that of the non-impaired hand (3065 ms).

General discussion

The primary aim of the present experiment was to study bimanual coordination in subjects exhibiting spastic hemiparesis. The results obtained in unimanual conditions were consistent with those reported previously for subjects with unilateral cerebral lesions (e.g. Trombly 1992; Jeannerod 1988; Fisk and Goodale 1988; Brown et al. 1989). Movements of the impaired hand required longer to initiate and to complete than those of the non-impaired hand.

The present experiment went beyond previous studies in also examining patterns of bimanual coordination. It was noted that the large asymmetries present in unimanual conditions were appreciably diminished in bimanual conditions in which subjects were required to move the impaired and the non-impaired limb to separate targets. Specifically, close synchrony of both response initiation and response execution was observed.

A reduction in the reaction time advantage for the non-impaired hand, during bilateral responding, was first reported by Jung and Dietz (1975). Consistent with the outcomes of the present study, Jung and Dietz noted that, in a bimanual task, subjects with unilateral lesions of the motor cortex initiated movements of their non-impaired limb simultaneously with movements of their impaired limb. However, contrary to the present results, subjects in the Jung and Dietz study reduced the advantage of the non-impaired limb primarily by decreasing the time to initiation of the impaired limb.

The tight temporal coupling of movement execution evident in the present study is also in concordance with the data reported by Sugden and Utley (1995). However, the manner in which the coupling was established in their study differed from that observed in the present study. Sugden and Utley (1995) noted that on some occasions the execution time of the impaired hand was reduced in bimanual conditions, while on other occasions the execution time of the non-impaired hand was increased.

Vagaries in the manner in which temporal coupling is established in the Jung and Dietz (1975) study, Sugden and Utley (1995) study and present study might well be due to the inhomogeneity both between and within patient groups. With respect to the latter, while all the subjects in the present study were diagnosed as having spastic hemiparesis their aetiologies were varied (Table 1). In addition, task differences between the studies might contribute to the different manners in which coupling between the limbs is accomplished.

Researchers working within the framework of action theory (e.g. Turvey 1977) have proposed that the simultaneous activation of homologous muscle groups, and the temporal invariance of the limbs to which this gives rise, is indicative of a coordinative structure form of control (e.g. Kelso et al. 1983). In this view, it is proposed that the limbs are constrained to act as a single task or functionally specific unit. It is believed that this form of organization simplifies the problem posed for the central nervous system, by reducing the number of degrees of freedom which must be actively controlled (Bernstein 1967). A related phenomenon, characterized by freezing of the joints and an enlargement of the postural contribution, with increasing demands for precision, has recently been demonstrated in a unimanual prehension task (Steenbergen et al. 1995b). In the present study a high temporal invariance between the two arms was found upon bimanual responding. This strongly suggests a coordinative structure type of control in which both arms are constrained to act as a single unit, thereby enhancing control

since only parameterization of this single ensemble needs to be performed.

There is also a good deal of neurobehavioural research relevant to the present findings. In general, symmetrical limb movements appear to be particularly well preserved after cortical lesions outside the primary motor cortex (e.g. Preilowski 1990; for an overview of experimental findings see Wiesendanger et al. 1994). It has also been shown that split-brain patients exhibit difficulty in performing asymmetrical movements, and show a greater attraction to symmetrical patterns than non-patients (Tuller and Kelso 1989).

In addition, there is extensive evidence to suggest that the motor systems subserving control of the trunk and of the proximal limb musculature are organized on a bilateral basis (e.g. Kuypers and Brinkman 1970; Brinkman and Kuypers 1973; Di Stefano et al. 1980; Aglioti et al. 1993; for an overview see Wiesendanger et al. 1994). Di Stefano et al. (1980) found "crossed-uncrossed" differences for distal bimanual responses to a lateralized flash, but not for proximal bimanual responses. These authors argue that control of the crossed distal musculature utilizes interhemispheric transfer, whereas control of the proximal musculature does not (see also Kuypers and Brinkman 1970; Brinkman and Kuypers 1973). The results of the study of a callosotomized subject by Aglioti et al. (1993) showed a similar pattern of results. Unimanual and bimanual distal responses resulted in large crossed-uncrossed differences in reaction time. In contrast, bimanual responses involving axial and proximal muscles showed no crossed-uncrossed differences in reaction time (see also Berlucchi et al. 1995).

The temporal coupling of the limbs which was evident in the present study also suggests the presence of bilateral control. In this instance it was not possible to determine the relative contribution of the proximal and distal musculature to the reach-grasp-placement task. However, preliminary work conducted recently in our laboratory suggests that the asymmetries present in unimanual conditions are due largely to a failure to control the distal musculature of the impaired limb. It is this facet of response execution which appears to be facilitated during bimanual movements, although residual differences in timing remain. Activation of the proximal musculature is closely synchronized (Steenbergen et al. 1995a).

It is also possible that "neural crosstalk" between contralateral and ipsilateral pathways, occurring at different levels of the central nervous system, may promote synchronicity of movement (e.g. Carson 1995). In particular, such mechanisms may account for our observation that, in bimanual conditions, the rate of movement of the non-impaired limb was reduced to that of the impaired limb. Explanations along similar lines have been put forward by Marteniuk et al. (1984) and Swinnen et al. (1991). When subjects are required to move a weighted and an unweighted stylus to a target, "assimilation" or synchronization effects are observed (Marteniuk et al. 1985, experiment 2). However, Marteniuk et al. maintain that

"the development and learning of bimanual skills involves the elimination (insulation) or incorporation of neural crosstalk, depending on the task requirements" (p. 363). It was a feature of the present study that the deficit of the impaired limb tended to be re-established when the spatial demands of the task were increased. The extent to which the impaired limb lagged the non-impaired limb was greatest in the bimanual conditions in which the impaired limb approached the small target and the non-impaired limb moved to the large target. These data suggest that further increases in the spatial accuracy demands of the task may precipitate a complete decoupling of the limbs.

Nevertheless, the present experiment showed that even subjects suffering from spastic hemiparesis, who exhibit large performance asymmetries when moving each hand independently, are able to achieve a high degree of coordination when moving both hands together. The implications of these findings for therapy and rehabilitation demand further study.

Acknowledgements This paper was written while the first author was supported by a grant from the Dr. W.M. Phelps-Stichting voor spastici (grant no. 92-048). We are grateful to Dr. R.G.M. Meulenbroek, Dr. R.G. Carson and two anonymous reviewers for providing helpful comments on an earlier draft of this manuscript.

References

- Aglioti S, Berlucchi G, Pallini R, Rossi GF, Tassinari G (1993) Hemispheric control of unilateral and bilateral responses to lateralized light stimuli after callosotomy and in callosal agenesis. *Exp Brain Res* 95: 151–165
- Barnes M, McLellan, L, Sutton R (1994) Spasticity. In: Greenwood RJ, Barnes MP, McMillan TM, Ward CD (eds) *Neurological rehabilitation*. Edinburgh: Churchill Livingstone, pp 161–172
- Berlucchi G, Aglioti C, Marzi CA, Tassinari G (1995) Corpus callosum and simple visuomotor integration. *Neuropsychologia* 33: 923–936
- Bernstein NA (1967) *The co-ordination and regulation of movement*. Pergamon, New York
- Brinkman, J, Kuypers HGJM (1973) Cerebral control of contralateral and ipsilateral arm, hand, and finger movements in the split-brain rhesus monkey. *Brain* 96: 653–674
- Brown JV, Schumacher U, Rohlmann A, Ettlinger G, Schmidt RC, Skreczek W (1989) Aimed movements to visual targets in hemiplegic and normal children: Is the "good" hand of children with infantile hemiplegia also normal? *Neuropsychologia* 27: 283–302
- Carson RG (1995) The dynamics of isometric bimanual coordination. *Exp Brain Res* 105: 465–477
- Di Stefano M, Morelli M, Marzi CA, Berlucchi G (1980) Hemispheric control of unilateral and bilateral movements of proximal and distal parts of the arm as inferred from simple reaction time to lateralized light stimuli in man. *Exp Brain Res* 38: 197–204
- Fisk JD, Goodale MA (1988) The effects of unilateral brain damage on visually guided reaching: hemispheric differences in the nature of the deficit. *Exp Brain Res* 72: 425–435
- Fitts PM (1954) The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol* 47: 381–391
- Fowler B, Duck T, Mosher M, Mathieson B (1991) The coordination of bimanual aiming movements: evidence for progressive desynchronization. *Q J Exp Psychol [A]* 43: 205–221
- Goodman D, Kobayashi RB, Kelso JAS (1983) Maintenance of symmetry as a constraint in motor control. *Can J Appl Sport Sci* 8: 238
- Jeannerod M (1988) *The neural and behavioural organization of goal-directed movements*. Oxford University Press, New York
- Jung R, Dietz V (1975) Verzögerter Start der Willkürbewegung bei Pyramidenläsionen des Menschen. *Arch Psychol Nervenkr* 221: 87–109
- Kelso JAS, Southard DL, Goodman D (1979a) On the coordination of bimanual movements. *J Exp Psychol* 5: 229–238
- Kelso JAS, Southard DL, Goodman D (1979b) On the nature of human interlimb coordination. *Science* 203: 1029–1031
- Kelso JAS, Putnam CA, Goodman D (1983) On the space-time structure of human interlimb coordination. *Q J Exp Psychol [A]* 35: 347–375
- Kuypers HGJM, Brinkman, J (1970) Precentral projections to different parts of the spinal intermediate zone in the rhesus monkey. *Brain Res* 24: 29–48
- Marteniuk RG, MacKenzie CL, Baba DM (1984) Bimanual movement control: information processing and interaction effects. *Q J Exp Psychol [A]* 36: 335–365
- Preilowski BFB (1990) Intermanual transfer, interhemispheric interaction and handedness in man and monkeys. In: Trevarthen C (ed) *Brain circuits and functions of the mind*. Cambridge University Press, Cambridge, pp 168–180
- Steenbergen B, Marteniuk RG, Kalbfleisch LE (1995a) Achieving coordination in prehension: Joint freezing and postural contributions. *J Mot Behav* 27: 333–348
- Steenbergen B, Hulstijn W, Vries A de, Berger M (1995b) Asymmetry effects in subjects with spastic hemiparesis. Paper at the VIIIth International Conference on Perception and Action, Marseille, 9–14 July
- Sugden D, Utley A (1995) Interlimb coupling in children with hemiplegic cerebral palsy. *Dev Med Child Neurol* 37: 293–309
- Swinen SP, Young DE, Walter CB, Serrien DJ (1991) Control of asymmetrical bimanual movements. *Exp Brain Res* 85: 163–173
- Trombly CA (1992) Deficits of reaching in subjects with left hemiparesis: a pilot study. *Am J Occup Ther* 46: 887–897
- Tuller B, Kelso JAS (1989) Environmentally-specified patterns of movement coordination in normal and split-brain subjects. *Exp Brain Res* 75: 306–316
- Turvey MT (1977) Preliminaries to a theory of action with reference to vision. In: Shaw R, Bransford J (eds) *Perceiving, acting and knowing*. Hillsdale, NJ: Erlbaum, pp 211–265
- Twitchell TE (1958) The grasping deficit in spastic hemiparesis. *Neurology* 8: 13–21
- Wiesendanger M, Wicki U, Rouiller E (1994) Are there unifying structures in the brain responsible for interlimb coordination. In: Swinnen S, Heuer H, Massion J, Casaer P (eds) *Interlimb coordination: neural, dynamical, and cognitive constraints*. Academic Press, San Diego, pp 179–207
- Wilcock R (1982) *Manual abilities scanning tests, MAST-1* Studieboek. DGSW, Rotterdam