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# The "Mirror Box" Illusion: Effect of Visual Information on Bimanual Coordination in Children with Spastic Hemiparetic Cerebral Palsy

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The study examined symmetrical bimanual coordination of children with spastic hemiparetic cerebral palsy (SHCP) and a typically developing (TD) control group under conditions of visual feedback created by placing a glass screen, opaque screen or a mirror ("mirror box") between the arms. The "mirror box" creates a visual illusion, which gives rise to a visual perception of a zero lag, symmetric movement between the two arms. Children with SHCP exhibited a similar mean coordination pattern as the TD control group, but had greater movement variability between the arms. Furthermore, movement variability in children with SHCP was significantly greater in the screen condition compared with the glass and mirror condition, which were similar to each other. The effects of the availability of visual feedback in individuals with hemiparesis are discussed with reference to central and peripheral mechanisms.

***Keywords:*** cerebral palsy, visual information, bimanual symmetry, children, kinematics

Cerebral palsy (CP) is a broad term that describes a group of congenital neurological brain disorders. A common form of CP is spastic hemiparetic cerebral palsy (SHCP), which is caused predominantly through unilateral damage to the motor cortex and/or pyramidal tract. Affected individuals have an increased muscle tone in certain antagonist muscle groups on the side of the body contralateral to the

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lesion. This leads to abnormalities in the muscle stretch reflex and higher velocity-dependent resistance during motion (Miller, 2005). In combination, these effects influence the motor behavior of individuals with SHCP such that they exhibit irregular or jerky movements of the contralateral limbs. Furthermore, while a unilateral cerebral lesion has greatest impact on the contralateral side, it has been reported that movement of limbs on the side ipsilateral to the lesion is also mildly impaired (Van der Weel, Van der Meer, & Lee, 1995). Still, it is notable that there is a strong asymmetry between body sides in individuals with SHCP, and hence the less impaired limb is often used as a "control" against which the more impaired limb can be compared (Steenbergen, Charles, & Gordon, 2008).

Many individuals with SHCP use their less impaired limb more frequently to compensate for the loss in functionality on their more impaired side (Taub, Crago, & Uswatte, 1998). However, although use of the less impaired limb presumably gives individuals some degree of immediate independence (Cauraugh & Summers, 2005), this might slow or even inhibit functional use of the more impaired limb in other contexts. Based on this reasoning, there have been two main approaches to therapy, which specifically aim to improve functional use of the more impaired upper limb. The first approach, known as the constraint-induced therapy, restrains movements of the less impaired limb by placing it in a sling, forcing individuals to use their more impaired limb (Taub et al., 1998). Restraint of the less impaired arm appears to be effective in overcoming learned nonuse in daily life activities (Taub et al., 1998). The second approach, known as bilateral movement rehabilitation, aims to facilitate functional use of the more impaired limb by symmetrically moving both limbs together and exploiting the natural tendency to synchronize movement frequency, amplitude and direction (Cauraugh & Summers, 2005). This has been particularly effective at improving coupling between the arms of children with hemiparetic CP when performing symmetrical bimanual movements (Steenbergen et al., 2008; Volman, Wijnroks, & Vermeer, 2002; Utley & Sugden, 1998; Sugden & Utley, 1995). For instance, when children with SHCP draw symmetrical circles with both hands, there is a decrease of temporal variability and an increase of smoothness of circle drawing (Volman et al., 2002). These findings have been taken to suggest that movement of the more impaired limb is adaptable and that this is at least partially based on a positive transfer from the less impaired arm (Steenbergen et al., 2008; Utley, Steenbergen, & Sugden, 2004).

While it was traditionally thought that muscular constraints limit the ability to perform bimanual coordination, it has been shown that manipulation of visual information can also exert an influence (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Shea, Buchanan, Kovacs, & Krueger, 2008). For example, it has been found that typically developed (TD) adults were able to easily perform highly complex bimanual movements (i.e., ratio of 4:3, 2:1 and 3:2 between the arms) when visual feedback was manipulated such that it represented a simple 1:1 circular ratio of the arms (Mechsner et al., 2001). An interesting possibility, therefore, might be that manipulation of visual information can also influence the movement of an individual with hemiparesis. For example, when looking at a mirror placed between the arms, the reflection of the nonparetic arm becomes a superimposition on the paretic arm, resulting in an illusory visual perception of a zero lag, symmetric movement between the two nonparetic limbs (Stevens & Stoykov, 2003, 2004; Franz & Packman, 2004). Some preliminary evidence for this position was shown in a study by

Altschuler, Wisdom, Stone, Foster, Galasko, Llewellyn and Ramachandran (1999) that had adults with hemiparesis following a stroke spend four weeks practicing bilateral movement in a "mirror box" or control (transparent plastic) condition. It was reported that there were substantial improvements in range of motion, speed, and accuracy of the paretic arm movement following "mirror box" therapy compared with the control treatment. Furthermore, in a later case study by Stevens and Stoykov (2003), two adult participants with chronic hemiparesis were found to show marked and lasting (i.e., 3-months) improvements in clinical assessments of the paretic wrist functionality and movement time following "mirror box" therapy. The implication, therefore, is that with the manipulation of visual feedback, movement difficulties could be overcome and the use of the paretic arm relearned in adults following a stroke (Altschuler et al., 1999; Stevens & Stoykov, 2003, 2004).

While case-studies on adults with movement difficulties arisen from hemiparesis due to stroke are encouraging, it is notable that there have been no previous attempts to determine whether manipulations of visual feedback using the "mirror box" lead to improved movement of the more impaired arm in children with SHCP. This is important because while these individuals also have overt asymmetries between the body-sides that affect their daily life, they may never have effectively learned to use their more impaired arm (Charles & Gordon, 2006). To this end, the current study employed an experimental setup similar to that used by Franz and Packman (2004), where a divide between the arms could be changed to manipulate the availability of visual information from the less impaired and more impaired upper limbs. Using this arrangement, visual information can be seen from both arms (glass condition), from one arm only (opaque screen condition), or from one arm and a mirror reflection ("mirror box" condition) that superimposes the arm behind the mirror.

The first aim of this study was to examine the coordination of the upper limbs when children with SHCP, and a TD age-matched control group, performed a symmetrical bimanual movement. Based on previous research, it was expected that both groups would be able to exhibit a symmetrical coordination pattern (Volman et al., 2002; Robertson, 2001; Utley & Sugden, 1998; Steenbergen, Hulstijn, De Vries, & Berger, 1996; Sugden & Utley, 1995). However, the children with SHCP were expected to perform the movement with more variability between the arms than the TD control population (Volman et al., 2002; Steenbergen et al., 1996).

Having determined the underlying coordination of the upper limbs in these two groups, the second aim was to examine the effects of specific manipulations of visual feedback using the "mirror box". It was expected that the absence of visual feedback of the more impaired arm in the screen condition would have a detrimental effect on coordination in children with SHCP because they could only rely on distorted proprioceptive feedback (Van der Weel et al., 1995). Furthermore, based on previous observations made in adults with hemiparesis (Altschuler et al., 1999; Stevens & Stoykov, 2003, 2004), it was predicted that the illusory visual perception of a zero lag, symmetric movement between two limbs in the mirror condition would have a beneficial effect on coordination. Finally, given that in TD adults no effect of visual manipulation was found on temporal measures of bimanual coordination (Franz & Packman, 2004), and further that there is no reason to believe that TD children in the current study would exhibit movement asymmetries, it was anticipated that this group would perform equally well in the three conditions.

# Methods

## Participants

The participants with SHCP were 8 children (mean age 13.9 years, *SD* = 2.9 years, age range = 9–18 years, 6 males and 2 females), who had no history of another neuromuscular disorder. Except for one, all participants indicated that their left arm was less affected than the right arm. The age-matched controls consisted of 14 TD children (mean age 13.8 years, *SD* = 3.0 years, age range = 9–18 years, 9 males and 5 females), all of whom indicated that they were right arm dominant and had no history of a neuromuscular disorder. The individual characteristics of the SHCP and TD children are presented in Table 1. Participants were excluded from the study if they had any pain in either of their upper limbs, an uncorrected visual impairment or could not adhere to the required task. The experiment was conducted in accordance with the Declaration of Helsinki. Written informed consent was given by the participants’ parents and written informed assent was obtained from all participants. The institutional research ethics committee approved all procedures.

## Materials and Procedure

A divide (width 0.06 m, depth 0.75 m, height 0.39 m) was securely placed between two custom-built wooden boxes (width 0.59 m, depth 0.17 m, height 0.39 m). The divide was a transparent screen (glass condition), an opaque screen (screen condition) or a mirror (mirror condition). The participant sat on a height-adjustable stool and placed one arm on either side of the divide and angled their head toward the side of their dominant/less impaired arm (Figure 1). In this position, each participant sat with both feet flat on the floor, knees flexed to 90° and elbows flexed to 90°. Participants then gripped in each hand a handle from an arm ergometer (871E, Monark Exercise AB, Vansbro, Sweden) that was attached to the edge of a wooden disc with a radius of 0.10 m, such that it spun freely through 360° around a vertical axis. The axes were fixed to a wooden table top (width 0.60 m, depth 0.46 m, height 0.04 m) and were located 0.31 m apart. If a participant was unable to grip the handle because of physical impairment, the hand was placed on top of the handle by the experimenter. Two serially-connected motion analysis units each containing three infrared cameras (3020 Optotrak, Northern Digital Inc., Waterloo, Canada) were used to measure the 3D position of the wrists at a sample rate of 200 Hz. Light emitting diodes were bilaterally attached to the skin with double-sided tape over the dorsal tuberculum of the radius (wrist). Pilot studies showed that participants were able to maintain an anatomical neutral position of the wrist during the movement, which ensured reliable recordings.

Before commencing the task, the arms were placed at a start position where they were at the inner most part of each of circle (i.e., nine o’clock for the right arm and three o’clock for the left arm). The participants were then asked to perform an inward, symmetrical circular movement of both upper limbs (i.e., the right arm rotated anticlockwise and the left arm rotated clockwise irrespective of hand dominance), and maintain this coordination mode throughout the experiment. In addition, participants were instructed to rotate the discs continuously at a self-selected pace

**Table 1 Information on the Children with SHCP and Their Age-Matched Control(s).**

| Participant | Age (Years) | Gender | More Impaired Arm | Severity AS / GMFCS / WeeFIM | Etiology | Matched Control Participant (Age / Gender / Arm Dominance) | |
|---|---|---|---|---|---|---|---|
| 1 | 16.3 | F | Left | 1 / 1 / 79 | $O_2$ shortage during birth | 16.8 / F / R | - |
| 2 | 17.1 | M | Right | 2 / 1 / 91 | Cerebral hemorrhage | 17.6 / F / R | 16.2 / M / R |
| 3 | 9.3 | F | Right | +1 / 1 / 89 | Cerebral hemorrhage | 9.6 / M / R | 9.3 / M / R |
| 4 | 11.0 | M | Right | 1 / 2 / 55 | Meningitis just after birth | 10.0 / F / R | 10.6 / M / R |
| 5 | 12.8 | M | Right | 1 / 1 / 90 | Unknown | 12.4 / F / R | 12.8 / M / R |
| 6 | 13.2 | M | Right | 1 / 1 / 91 | Unknown | 14.0 / F / R | - |
| 7 | 17.4 | M | Right | 1 / 1 / 90 | $O_2$ shortage during birth | 16.7 / M / R | 17.2 / M / R |
| 8 | 14.3 | M | Right | +1 / 1 / 91 | Cerebral hemorrhage during birth & Meningitis just after birth | 14.8 / M / R | 14.6 / M / R |

*Note*. Severity of the child's impairment was assessed by a single experimenter using the modified Ashworth scale (AS) for the elbow (range: 0–5, higher scores denoting more spasticity), gross motor function classification system (GMFCS; range 1–4, higher scores denoting less gross motor functionality) and functional independence measure for children (WeeFIM; motor items only, range: 13–91, higher scores denoting more functional independence of the child).

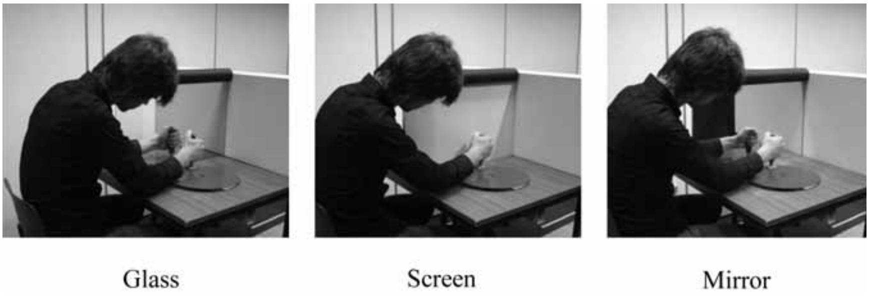


**Figure 1** — Experimental set up of the "mirror box" during the glass (left panel), screen (middle panel) and mirror (right panel) condition when the participant's head is positioned toward their dominant arm side to view the bimanual task.

after the start instruction was given and until they were instructed to stop. They were also requested to keep their self-selected pace (i.e., movement frequency) constant during the experimental trials, which each lasted approximately 15 s. Before data collection, practice trials were conducted to familiarize the participant with the protocol and test setup.

In experimental trials, participants performed the bimanual coordination task in three conditions that differed according to the divide placed between the arms. Three trials per condition were recorded and the condition order was pseudo-randomized across participants. To keep the point of gaze constant between trials, a reference dot was placed between the start position and the divide. Participants were asked to keep the reference point in their central viewing area while performing each trial to prevent them focusing on one arm only during the screen condition. To recover from any fatigue or drop in concentration that might have occurred during the experiment, participants were given short breaks between trials. To keep the participants motivated, they were told that rotating the handles symmetrically would result in more points being scored, and that at the end of the experiment they could trade the points for a small gift.

## Data Analysis

2D kinematic data from the wrist were analyzed from the first 2 cycles completed by the participant in each trial. The first two cycles of each trial were analyzed because some children with SHCP could only produce 2 cycles before they adopted a coordination mode that was different to the one they were instructed to produce (e.g., outward rotation of the handles or a transition from a symmetric to an asymmetric coordination). These changes away from the required coordination would have disproportionately influenced the variability of the relative phase (Volman et al., 2002), and hence they could not be included in the analysis. Moreover, for some of the children with SHCP, movement time only allowed them to complete 2 cycles within the allocated time of each trial, or the hand slipped of the handle at which point the trial was terminated. Overall, in the TD group of children, 5 out of 126 trials were excluded from analysis, whereas in the children with SHCP, 18 out of 72 trials were excluded.

The duration of the 2 cycles was determined to enable calculation of movement time. Interlimb coupling was assessed based on both position and velocity of the two limbs (Kelso, 1995). The phase portrait obtained when the position of each limb was plotted against its velocity allowed calculation of the continuous relative phase (CRP) of each limb separately, according to the following formulas:

$$\varphi D = \arctan\left[(dS_D \cdot dt^{-1}) / S_D\right]$$

and

$$\varphi ND = \arctan\left[(dS_{ND} \cdot dt^{-1}) / S_{ND}\right],$$

where φD and φND are the phase of the dominant and nondominant arm respectively, and $S_D$ and $S_{ND}$ are the position time series and $dS_D \cdot dt^{-1}$ and $dS_{ND} \cdot dt^{-1}$ represent instantaneous velocity. Before the calculation of φND, the sign of the position time series of the nondominant arm was inversed to an anticlockwise trajectory. The CRP indicated the degree of coupling (i.e., synchronicity) between the arms and denoted by Φ, was derived from:

$$\Phi = \varphi D—\varphi ND,$$

where a positive value for Φ implied a dominant arm lead and a negative value a nondominant arm lead. Moreover, $\Phi = 0°$ indicates perfect symmetrical and $\Phi = 180°$ indicates perfect asymmetrical coordination, which means that the limbs were behaving in exactly the same or opposite way, respectively. The mean and standard deviation (*SD*) of the CRP during the two cycles were calculated for each trial to assess the temporal relation and its variability between the arms.

In addition, it was deemed important to determine if changes in bimanual coordination as a result of manipulating visual feedback reside in the more impaired arm alone or in both the more and less impaired arm. A reduction in symmetric coordination caused by improperly timed initiation and disproportionate activation of independent muscle system, for example as a result of spasticity, is likely to result in multiple acceleration peaks. This can be measured as an increase in jerk compared with when coordination is regular and smooth (Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; Flash & Hogan, 1985). Mean jerk over the 2 cycles (unit: position/time$^3$) was calculated in both medial/lateral direction (x—axis) and posterior/anterior (y—axis) direction by taking the third derivative of the x—and y—position. Before jerk was calculated, position time signals of each trial were filtered with a bidirectional 2nd order Butterworth filter. The cut-off frequency was determined by taking 1 Hz lower than the frequency ascertained with the residual analysis. A lower cut-off frequency was taken to obtain a 'smoother' higher derivative of position data (Giakas & Baltzopoulos, 1997). The range of the cut-off frequency was 2–10 Hz.

The level of jerk depends on the size and the duration of the movements (Teulings et al., 1997), which in the current study could have differed between participants because of their different anatomical proportions and preferred movement time. Therefore, to compare intralimb stability between participants, jerk was normalized for different size and duration of movements in each trial (i.e., 2 cycles). This was done by multiplying the integrated square jerk by time$^5$/position$^2$ and subsequently the square root was taken so that normalized jerk was proportional with absolute jerk. Normalized jerk is a unit less measure and described with:

$$Normalized \quad jerk = \sqrt{(\tfrac{1}{2} \int dtj^2(t) \bullet time^5 / position^2)}$$

## Statistical Analyses

The values for mean CRP could in theory range from +180° to -180°, both of which represent perfect asymmetrical coordination mode. Usually circular statistics would be used to obtain a measure of dispersion with this type of variable. However, in the current study, participants were asked to keep the end effectors as symmetrical as possible in an in-phase coordination mode. Therefore, in practice, the values were in the range of +90° and -90°, which implied that normal distribution statistics could be used. Group data of mean CRP, *SD* CRP and movement time were submitted to separate mixed ANOVA with one repeated factor, divide (3 levels), and one independent factor, group (2 levels). In addition, the mean jerk data were submitted to a mixed ANOVA with two repeated factors, arm (2 levels) and divide (3 levels), and one independent factor, group (2 levels). In cases where the sphericity assumption was violated, Greenhouse-Geisser adjustments were made. Fishers' LSD was used for post hoc analysis, and the alpha-level was set at 0.05. Effect size ($\omega^2$) data were calculated according to Field (2005) and standard error was reported to indicate the true mean variability.

# Results

There was no significant difference between the groups for mean CRP (TD = -4.4 ± 3.3°; SHCP = -0.3 ± 4.4°) or movement time (TD = 3.01 ± 0.45 s, range = 1.45–7.82 s; SHCP = 3.50 ± 0.59 s, range = 1.43–9.66 s). This indicates that the children with SHCP were able to maintain a similar coordination pattern (mean CRP) as the TD children, and that both groups lead with the non dominant/more impaired arm. However, as seen in Figure 2, children with SHCP exhibited significantly higher *SD* CRP [$F(1,20) = 22.67$, $p < .01$, $\omega^2 = .53$] compared with the TD children.

There were no significant differences between the divides for mean CRP (glass = -1.0 ± 2.8°; screen = -2.9 ± 3.6°; mirror = -3.0 ± 3.1°) or movement time (glass = 3.10 ± 0.39 s, range = 1.43–9.66 s; screen = 3.39 ± 0.46 s, range = 1.43–9.32 s; mirror = 3.28 ± 0.33 s, range = 1.45–8.07 s). In addition, there was no significant group by divide interaction for these variables [all: $p > .49$]. However, there was a significant main effect of divide for *SD* CRP [$F(1.4,28.1) = 4.91$, $p < .05$, $\omega^2 = .20$], as well as a significant group by divide interaction [$F(2,40) = 3.4$, $p < .05$, $\omega^2 = .15$], indicating that the two groups responded differently to the 3 divides (see Figure 2). Post hoc tests revealed that the variability of the coordination pattern (*SD* CRP) in the TD children was equal in all the conditions. In contrast, for children with SHCP, *SD* CRP was significantly higher in the screen condition compared with the glass and the mirror condition [$p < .01$ and $p < .05$, respectively]. Furthermore, *SD* CRP in the mirror condition did not differ significantly from the glass condition [$p > .23$].

Results for normalized jerk showed that the mean for one child with SHCP was twice the value of the group mean, hence this participant was considered as

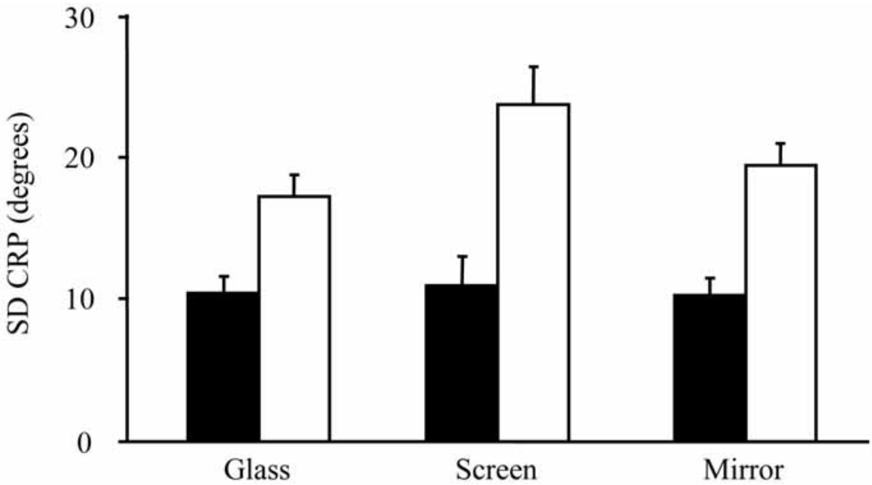


**Figure 2** — Standard deviation of the continuous relative phase of the control (solid) and the SHCP group (open) during the glass, screen and mirror condition of the "mirror box". Error bars (*SE*) indicate true mean variability.

an outlier and excluded from the analysis. In the remaining data, there was no significant main effect of group or divide for normalized jerk in the medial/lateral direction or posterior/anterior direction [all: $p > .19$]. There was a significant main effect for arm [$F(1,19) = 16.8$, $p < .01$, $\omega^2 = .47$; $F(1,19) = 13.1$, $p < .01$, $\omega^2 = .41$, for medial/lateral and posterior/anterior direction, respectively], as well as a significant group by arm interaction [$F(1,19) = 15.7$, $p < .01$, $\omega^2 = .45$; $F(1,19 = 11.4$, $p < .01$, $\omega^2 = .38$; see Figure 3]. Post hoc analyses of the group by arm interaction revealed that normalized jerk in the more impaired arm of children with SHCP was significantly larger than in the less impaired arm in both the medial/lateral direction [$p < .01$; 230.6 and 475.4, respectively] and in the posterior/anterior direction [$p < .01$; 217.6 and 375.0, respectively]. In TD children, however, there was no difference between the dominant and non–dominant arm in the medial/lateral direction (240.5 and 244.8, respectively) or the posterior/anterior direction (223.2 and 228.6, respectively). No other significant interactions were found for normalized jerk [all: $p > .28$].

## Discussion

The current experiment examined coordination of the upper limbs when children with SHCP and a TD age-matched control group performed a symmetrical bimanual movement under conditions of different visual feedback. Consistent with results from experiments that have examined bimanual reach and grasp tasks (Steenbergen et al., 1996; Sugden & Utley, 1995), it was found that for the first two cycles of a

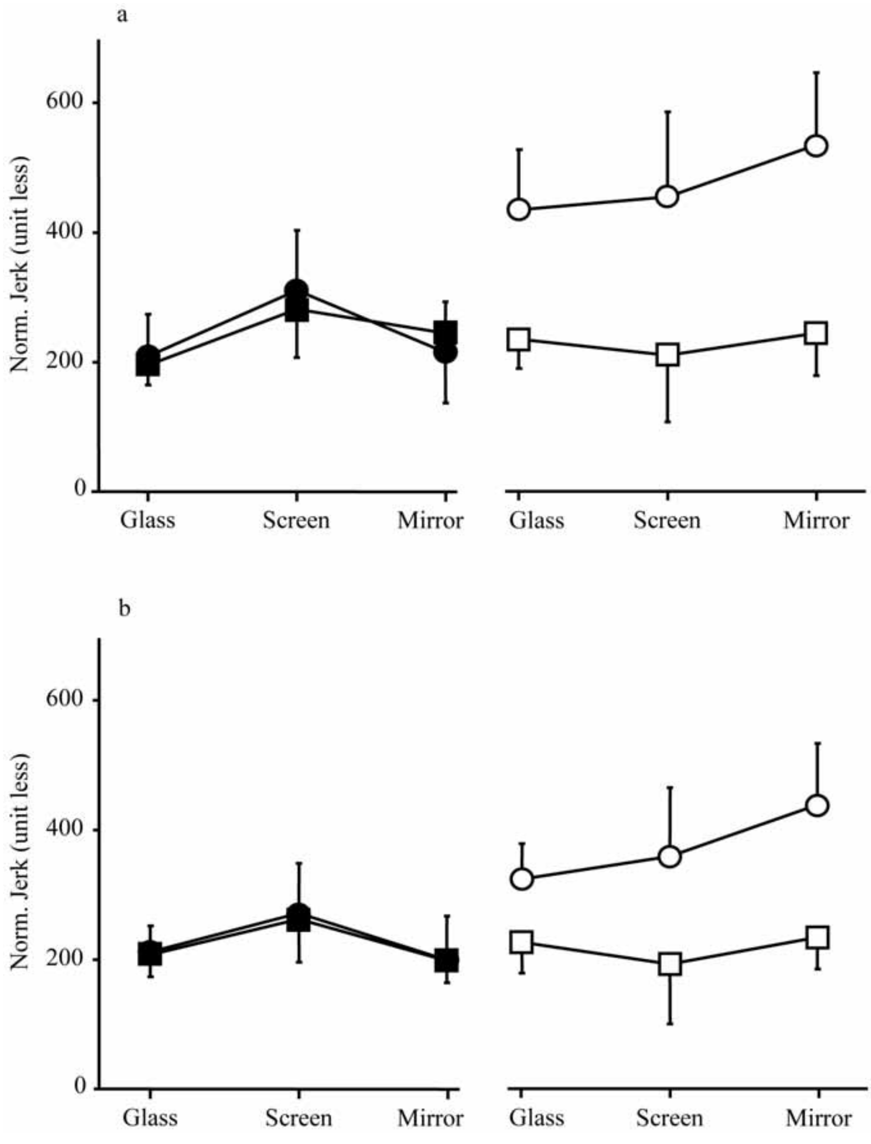


**Figure 3** — Mean normalized jerk in the dominant/less impaired arm (squares) and non-dominant/more impaired arm (circles) for TD children (solid) and children with SHCP (open) during the glass, screen and mirror condition in the a) medial/lateral direction and b) posterior/anterior direction. Error bars (*SE*) indicate true mean variability.

bimanual circular movement, children with SHCP were able to maintain a similar mean temporal coordination pattern (i.e., mean CRP and movement time) compared with an age-matched control group. However, children with SHCP showed greater variability of the coordination pattern (i.e., *SD* CRP) compared with the TD children, and exhibited increased normalized jerk in the more impaired arm compared with the less impaired arm. The level of bimanual variability exhibited by SHCP children in the current study was similar to that reported by Volman et al. (2002). In combination, therefore, these results confirm that while differences in bimanual movement capabilities exist between children with SHCP and TD children, for the first 2 complete cycles, children with SHCP can complete the overall goal of the task (i.e., symmetrical bimanual movements).

In addition to determining the underlying coordination of the upper limbs in these two groups, the current study also enabled us to investigate how this was affected by the availability of visual information from the less impaired and more impaired upper limbs. As expected, there was no difference in the measures of bimanual coordination as a function of visual feedback (i.e., divide) for the TD children (see Franz & Packman, 2004). For the SHCP children, however, despite there being no difference in mean temporal coordination pattern or movement time across the three conditions, there was an increase in interlimb movement variability in the opaque screen condition; bimanual coordination in the mirror condition did not differ from the glass condition. These results indicate that the SHCP children had difficulties maintaining a stable interlimb coupling when visual information of the impaired arm was absent. Furthermore, providing SHCP children with the opportunity to see a mirror reflection of their less impaired arm resulted in levels of movement variability similar to that when performing in the glass condition. The important point to note, therefore, is that while no beneficial effects of performing in the "mirror box" were found (see Altschuler et al. 1999), there were also no negative effects of substituting the veridical information from the more impaired limb with a mirror reflection of the less impaired limb. Given that the visual feedback available in the mirror condition would have been the most unusual circumstance for children with SHCP (i.e., they perceived two less impaired arms), it will be important to next determine whether a more prolonged training protocol with the mirror could result in a reduced movement variability compared with the glass condition.

The effects of "mirror box" therapy in individuals with hemiparesis have been explained based on central or peripheral mechanisms. While it is not the intention here to discriminate which of these explanations better explain our results, it is relevant to consider each of these underlying mechanisms. A possible explanation for the described observations might be sought within the organization of the central nervous system. Garry, Loftus, and Summers (2005) found that when TD adults viewed their unimanual movements through a mirror, the excitability of M1 area of the inactive contralateral arm increased beyond that produced by ipsilateral hand movements alone. This suggests that an increase in cross-talk could occur from the intact brain hemisphere toward the damaged brain hemisphere. Future research with transcranial magnetic stimulation and functional magnetic resonance imaging of children with SHCP while using the "mirror box" might disclose further evidence to support the central mechanism explanation.

Alternatively, a possible peripheral mechanism involves a change in directed attention to the intact sensory feedback (i.e., vision) instead of distorted sensory feedback (i.e., proprioception). Indeed, for individuals with hemiparesis, it has been suggested that redirection of visual attention toward the sensory feedback of the more impaired arm might help individuals with hemiparesis to reduce movement disorders and future complications such as learned disuse (Sathian, Greenspan, & Wolf, 2000; Opila-Lehman, Short, & Trombly, 1985). The “mirror box” is thought to assist with the switch in attention because the visual signals received back from the superimposed image seen in the mirror correspond with the movements of the less impaired arm. In other words, an individual receives positive reinforced visual feedback from the superimposed image of intended movements (Ramachandran, 2005; Moseley, 2004). In line with this position, the work of Mechsner et al. (2001) shows that visual information is able to override muscular constraints when participants are instructed to perform highly complex bimanual coordination patterns (see also Tomatsu & Ohtsuki, 2005).

Although normalized jerk is not a direct measure for spasticity, it did present an opportunity to objectively quantify the movement difficulties that children with SHCP experienced in the more impaired arm. The greater amount of normalized jerk measured for the more impaired arm, confirms the detrimental asymmetric effect of SHCP. In addition, in contrast to the interlimb movement variability, there were no differences for normalized jerk in the arms of children with SHCP between the different visual manipulations. This indicates that the motor behavior of both the more and the less impaired arm did not change in the mirror condition, and therefore that the changes in movement variability in response to the visual manipulations cannot be explained by changes in normalized jerk of either arm alone. Direct measurement of the abnormalities of the upper limb neuromuscular activity during bimanual movement should be addressed with the use of electromyography in subsequent experiments.

Given the effect of handedness on the relative phase of bimanual coordination (Swinnen, Jardin, & Meulenbroek, 1996), it could be argued that the different distribution in hand dominance in the two groups (i.e., the children with SHCP were predominantly left hand dominant while the TD children were all right hand dominant) may have contributed to the findings of the current study. In previous research in adults, the dominant hand was demonstrated to be the leading limb in bimanual tasks with a smaller phase lag in left-handers than in right-handers (Amazeen, Amazeen, Treffner, & Turvey, 1997; Franz, Rowse, & Ballantine, 2002; Franz, 2004; Swinnen et al., 1996). It therefore seems surprising that the participants in the current study tended to lead the bimanual movement with their nondominant arm/more impaired arm. A possible explanation of this discrepancy may reside in the altered constraints imposed on arm movement (i.e., range of motion in the shoulder and elbow joints) due to the specific position of head, neck and, trunk that was required to perceive the visual illusion. In pilot data, it was found that when participants angled their head toward the side of their nondominant/more impaired arm, a switch in arm lead occurred (i.e., the arm on the contralateral side of the divide lead the movement), although more research is needed to confirm this observation. In addition, it should be acknowledged that hand dominance in children with SHCP might well be the result of other and additional lateralizing factors (i.e., muscle dysfunction due to neurological damage) than in TD children. Previous research has suggested that bimanual control is different and less lateralized in left-handers (e.g., Swinnen et al., 1996). However, given the potential distinction in the origin and significance of hand dominance in children with SHCP and TD children, the impact of handedness on bimanual control in the current study is difficult to ascertain and has yet to be determined.

It is well reported that children affected by SHCP exhibit an increased muscle tone in certain antagonist muscle groups that affects the muscle stretch reflex and higher velocity-dependent resistance on one side of the body during motion (Miller, 2005). This study has suggested that these effects of SHCP might have played an important part in the observation that some children with SHCP could only produce 2 cycles before they switched to a different coordination mode (e.g., from inward to outward or from symmetrical to asymmetrical). It is worth considering, however, that another related explanation could lie in the adopted timing control strategy as shown by Zelaznik et al. (2005). In a similar task it was found that during the early stages of continuous circle drawing of adults, control of the movement rapidly transited from event-based to emergent timing. It could be argued that children with SHCP have difficulties to adopt this emergent timing strategy where the movement is controlled on the basis of the task dynamics rather than specific time events. Future research is warranted to investigate if this event-based timing strategy was less optimal for this cyclic task and therefore a contributing factor for the fact that some children with SHCP could only perform 2 cycles.

In conclusion, the results from this exploration of acute effects on bimanual coordination, show that the upper limb movement of children with SHCP is more variable than that of TD children. In addition, children with SHCP show greater amounts of normalized jerk in the more impaired arm compared with the less impaired arm. The manipulation of visual information only affected movement variability in children with SHCP, which was significantly greater in the screen condition compared with the glass and mirror condition. These results are encouraging and warrant further investigation to establish if a period of sustained practice with the “mirror box” has any long-term benefits on bimanual coordination, as well as positive transfer to daily life activities.

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