Children with unilateral cerebral palsy show diminished implicit motor imagery with the affected hand

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This article is commented on by Cheron on pages 223–224 of this issue.

AIM Motor imagery refers to the mental simulation of a motor action without producing an overt movement. Implicit motor imagery can be regarded as a first-person kinesthetic perceptual judgement, and addresses the capacity to engage into the manipulation of one's body schema. In this study, we examined whether children with unilateral cerebral palsy (CP) are able to engage in implicit motor imagery.
METHOD A modified version of the hand laterality judgment task was employed. Erroneous responses, reaction times, and event-related potentials from the electroencephalograph were analysed.
RESULTS In 13 children with typical development (mean age 10y 7mo, SD 1y 2mo; seven male, six female), we observed the classic rotation direction effect. Specifically, when comparing outward rotated with inward rotated hand pictures, decreased accuracy and increased response times were observed. Event-related potentials analyses of the electroencephalogram revealed a more marked N1 and an enhanced rotation-related negativity.
INTERPRETATION These findings suggest that an implicit motor imagery strategy was used to solve the task. However, in 10 children with unilateral CP (mean age 10y 7mo, SD 2y 5mo; five male, five female), these effects were observed only when the less-affected hand was involved. This observation suggests that children with CP could benefit from visual training strategies.

Cerebral palsy (CP) describes a group of permanent disorders of movement and posture that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain.[1] In the current study we focused on children with unilateral CP with one hand being more affected than the other hand. Motor impairments associated with CP can be understood as a diminished ability of the brain to control complex motor programs.[2–5]

Motor imagery refers to the internal representation of an action without producing an overt body movement.[4–7] A distinction can be made between explicit and implicit motor imagery. During explicit motor imagery, a specific motor act is internally simulated, whereas implicit motor imagery refers to the ability to engage into the projection and manipulation of the body schema from a first-person perspective.[6–8] An often used paradigm to test the implicit motor imagery ability is Parsons' hand laterality judgement (HLJ) task.[6,9] In this forced choice task, participants judge the laterality of displayed hands as quickly as possible by determining whether a left or right hand is depicted. Typically, the reaction times increase more for hand pictures that are rotated outward than inward. Parsons[9] proposed that prolonged reaction times for outward rotated hands reflect the biomechanical constraints encountered when mentally rotating one's own hand to match the depicted hand stimulus. Thus, it is generally believed that participants engage in a kinesthetic mental rotation to solve the HLJ task.[6,7] This rotation effect has been repeatedly replicated since.[10–12]

In recent years, behavioral studies have emerged that scrutinize the motor imagery ability of individuals with CP.[13–15] It was concluded that although adolescents with CP are able to engage in mental rotation, the implicit motor imagery capacity seemed to be compromised. Recently, Williams et al.[14,15] found that children with unilateral CP were slower and less accurate on the HLJ task than a comparison group.[14,15]

Although implicit motor imagery has been extensively researched by analysing overt behavioural measures like

reaction times and response accuracy, these data reflect only the outcome of combined cognitive and response processes, rather than the isolated process itself. Extracting event-related potentials (ERPs) from the ongoing electroencephalogram (EEG), however, provides an excellent means to directly study the neural responses associated with implicit motor imagery.[11,12] ERP components are typically divided into two types, based on their respective latencies. Components with latencies of up to 100ms are referred to as exogenous components,[16] whereas the endogenous components (>100ms after stimulus onset) are assumed to be determined by cognitive aspects of information processing.[16] In the current study we focused on these endogenous components. Previous ERP studies have shown that mental rotation is accompanied by a negative-going amplitude modulation of the late-latency ERP components.[10–12] This modulation has been referred to as rotation-related negativity (RRN) and has been observed in several mental rotation studies.[10,11] Interestingly, RRN is more pronounced for outward rotated stimuli than for inward rotated stimuli.[11,12] These findings suggest that RRN, similar to reaction time, is also modulated by biomechanical constraints.[11,12]

Only a few studies have investigated implicit motor imagery by means of EEG measurements in patient groups. For example, Van Elk et al.[17] recorded the EEG of young adults with unilateral CP while they performed the HLJ task. Results revealed a reduced RRN over parietal areas and prolonged reaction times for the group with CP compared with controls. However, stroke patients with acquired hemiplegia seem to preserve their implicit motor imagery ability for both their paralyzed and nonaffected hands.[18,19]

Unlike stroke patients, adolescents and children with unilateral CP lack a typical early development of the body schema.[8] Moreover, their internal body representation might be less accurate with respect to the affected side of the body than the less-affected side. Because implicit motor imagery relies on the ability to engage into the projection and manipulation of the body schema from a first-person perspective, we hypothesize that in unilateral CP, implicit motor imagery is especially compromised when the affected hand is involved, but less so when the less-affected hand is involved.[7] To the best of our knowledge, previous research has never compared the implicit motor imagery capacity of the affected and less-affected hand separately in children with unilateral CP.

In the present study, our main aim was to determine if implicit motor imagery capacity is (partly) determined by the motor capacity of the involved hand. We did this by recording ERPs that were elicited in response to the Parsons' HJL task. Response accuracy and response speed were also measured.

METHOD

Ten children with unilateral CP (mean age 10y 7mo [SD 2y 5mo]; five male, five female; four left-hand affected, all with IQ scores >70) participated in the study (group with CP) and 13 children with typical development (mean age 10y 7mo,

What this paper adds
- Implicit motor imagery was studied in unilateral cerebral palsy.
- Behavioural data and event-related potentials quantified implicit motor imagery capacity.
- Children with unilateral cerebral palsy engaged in implicit motor imagery.
- However, implicit motor imagery was compromised for the affected hand.
- These findings might increase our understanding of body schema development.

SD 1y 2mo; seven male, six female; all right-handed) participated in the experiment. There was no evidence that groups differed in the proportion of each sex or the mean age.

An adapted version of Parson's HLJ task was employed[11] to study the implicit motor imagery ability. Participants' hands were covered with a cloth to prevent a visual matching strategy. Participants' hands were positioned over a large response button (diameter 9.5cm; height 5.5cm) to capture both the reaction times and laterality decisions. Visual stimuli, presented on the screen, consisted of photos of a child's left or right hand. The hand was seen from either a palm view or a back view perspective, and was rotated by 60° in either an inward or outward direction. This resulted in eight different stimuli (see Fig. 1a). Participants had to generate a response on presentation of a visual response screen, which was displayed after a fixed waiting interval of 1700ms (delayed response task). By introducing a delayed response, we expected motor imagery to be less distorted by cognitive processes related to response execution and concurrent motor artefacts. Participants were asked to judge the laterality of the displayed hands as quickly and accurately as possible after the response screen by pressing either the left or right response button. Participants were only instructed to judge the hand laterality and were not instructed to use motor imagery to solve the task. In total 96 trials were presented. The experiment lasted about 15 minutes. An example of the set-up of a trial is shown in Figure 1b.

EEG and electrooculographic signals were recorded with a 32-channel actiCap system (Brain Products GmbH, Munich, Germany). Electrodes were located on positions according to the international 10 to 20 system. Measured activity was referenced to linked mastoids.[10,20] A ground electrode was located at the AFz electrode position. Electrode impedance was kept below 5kΩ. Eye movements were recorded by electrodes placed below the right eye and at the outer canthus of the right eye. The signal was digitized online at 1000Hz, with high-pass and low-pass filters set at 0.1Hz and 100Hz respectively. For children with CP that were right-hand affected (n=4), the electrode positions were inverted (i.e. P3 was redefined as P4, etc.). The EEG was corrected for electrooculographic artefacts by employing the Gratton and Coles algorithm. High-pass and low-pass filters of 0.53Hz and 40Hz were subsequently applied. EEG data on trials with incorrect responses or trials contaminated with artifacts exceeding 150µVan amplitude of 150µV detected by automatic segment selection provided by Brain Vision Analyser were also excluded (for the children with typical development and group with CP
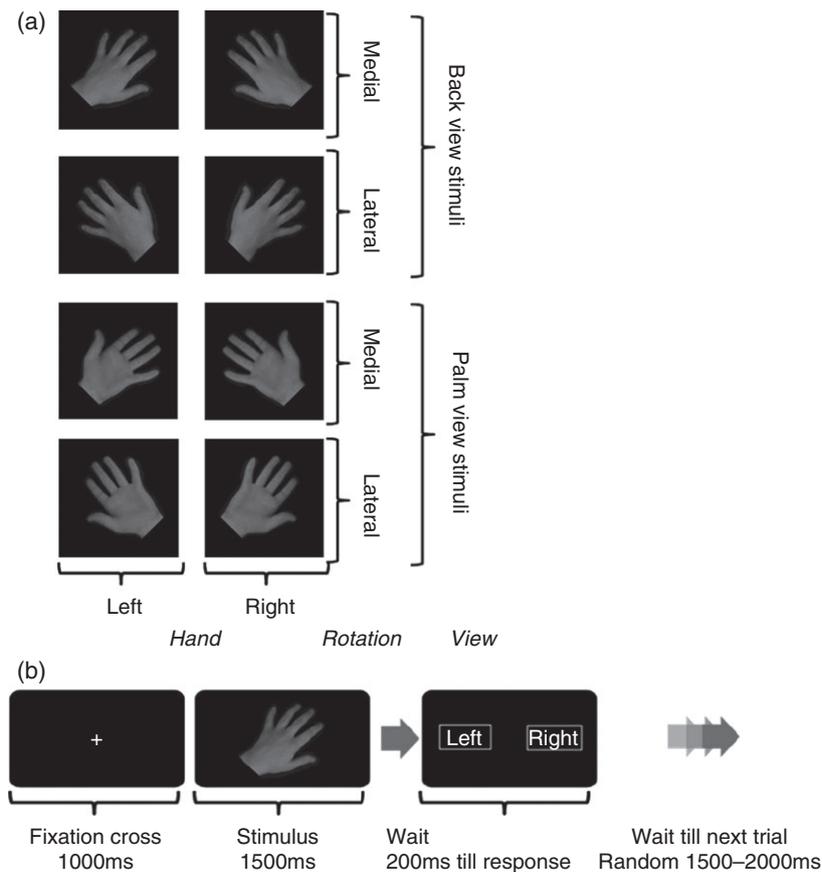
Figure 1: (a) Stimulus material. The eight different hand stimuli that were randomly presented during the experiment. (b) Task. Graphical representation of a trial in the adapted hand laterality judgment task.

4% and 12% of the total amount of trials respectively). A 250ms interval was used for baseline correction. Next, averages were computed per stimulus type. Grand average ERPs were additionally computed for each group, as displayed in Figure 2a,b.

Accuracy was determined by analysing the percentage of errors with a repeated measures ANOVA with the variables rotation (inward or outward rotation) and view (palm view or back view) as within participant factors, and group (CP or typical development) as between participants factor.

For average error percentage analysis, nonparametric Wilcoxon signed-rank test and Mann–Whitney U test were conducted since error data did not meet parametric assumptions. Reaction times were also analysed with a repeated measures ANOVA with the variables hand rotation and view as within participant factors, and group as between participants factor. Whenever interaction effects were observed, appropriate post hoc tests were performed.

After visual inspection of the grand average ERPs, the N1, P2, and RRN components could be identified. ERP amplitudes were determined as the average value within a fixed latency window (N1 140–160ms; P2 200–220ms; RRN amplitude 350–400ms; Fig. 2). The N1 and P2

appeared to be maximal over the frontal region and the data from F3/Fz/F4 were further analysed. The RRN effect seemed maximal over the parietal region and the data from P3/Pz/P4 were further analysed. ERP component amplitudes were analysed using a repeated measures ANOVA with the variables hand (left [nonpreferred] vs right [preferred] hand), rotation (inward vs outward rotation), view (palm view vs back view), and electrode position with respect to the presented hands stimulus (ipsilateral: F/P3 for left and F/P4 for right hand stimuli; central: F/Pz; contralateral: F/P3 for left and F/P4 for right hand stimuli). Group served as a between participants factor.

Informed consent was obtained before the start of the experiment and the procedures were approved by the local ethics committee (nr. ECG30062011).

RESULTS

With respect to the error analyses, three participants with unilateral CP were excluded from further analysis because their performance did not exceed chance levels. Error analyses of the remaining participants revealed a main group effect and a main view effect, which reflected increased error rates for the group with CP, and increased error rates for palm view stimuli. In addition, we observed
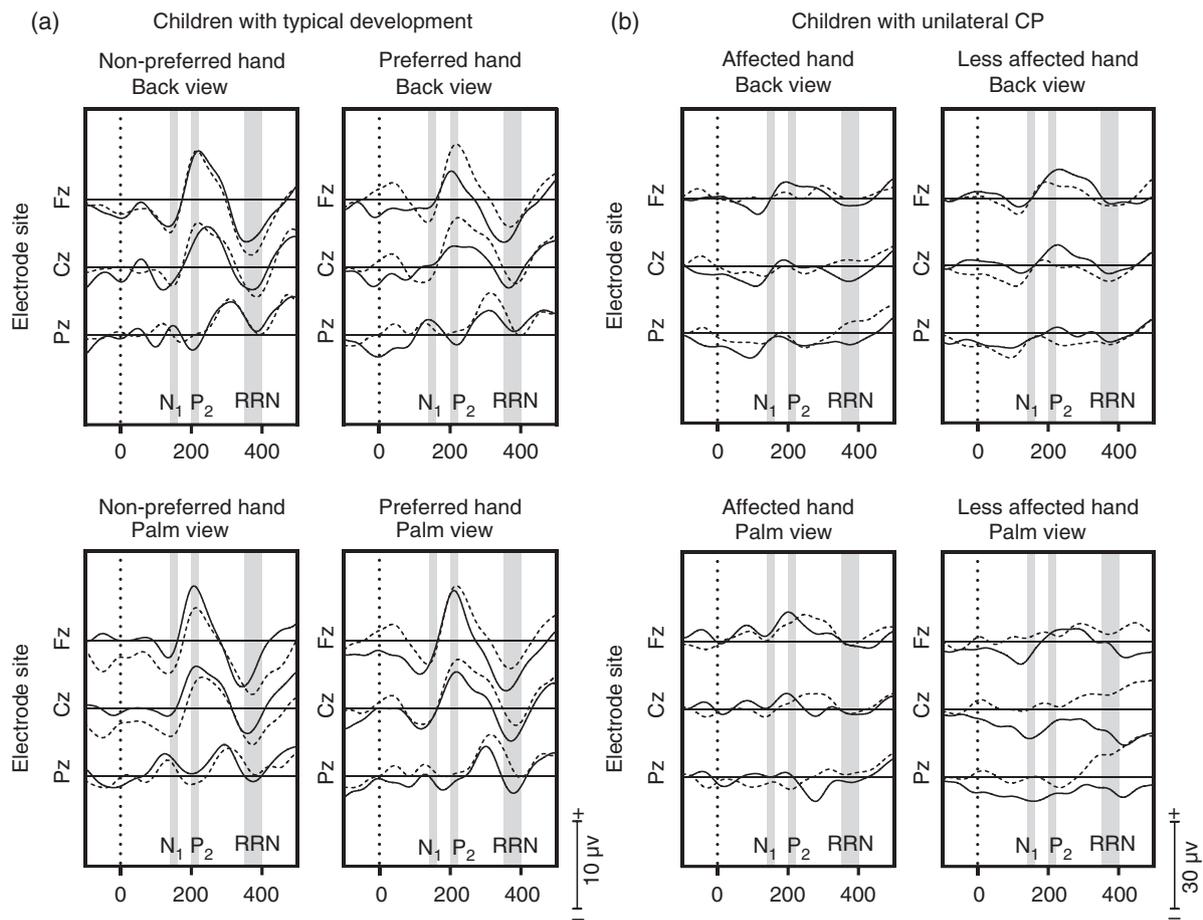
Figure 2: (a) Grand average event-related potentials (ERPs) of the group of children with typical development. ERPs are depicted for the midline electrodes Fz, Cz, and Pz on the *y*-axes. Medially rotated hand stimuli are depicted with a dotted line, whereas laterally rotated stimuli are depicted with a solid line. The *x*-axes show the time-related stimulus onset (in ms). Grey bars mark the N1, P2, and rotation-related negativity (RRN) latency windows. The upper panels show the ERPs for the back view stimuli, with ERPs to stimuli depicting the non-preferred hand on the left and ERPs to stimuli depicting the preferred hand on the right. The lower panels show the ERPs for the palm view stimuli, with ERPs to stimuli depicting the non-preferred hand on the left and ERPs to stimuli depicting the preferred hand on the right. (b) Grand average ERPs of the group of children with unilateral cerebral palsy (CP). ERPs are depicted for the midline electrodes Fz, Cz, and Pz on the *y*-axes. Medially rotated hand stimuli are depicted with a dotted line, whereas laterally rotated stimuli are depicted with a solid line. The *x*-axes show the time-related stimulus onset (in ms). Grey bars mark the N1, P2, and RRN latency windows. The upper panels show the ERPs for the back view stimuli with ERPs to stimuli depicting the affected hand on the left and ERPs to stimuli depicting the less-affected hand on the right. The lower panels show the ERPs for the palm view stimuli with ERPs to stimuli depicting the affected hand on the left and ERPs to stimuli depicting the less-affected hand on the right.

a group*hand interaction effect and a group*view interaction effect. Results were further analysed with nonparametric tests. The main effects of view and group remained significant, showing that children with CP made more errors than children with typical development. Within the group of children with typical development no further effects were observed. Participants with CP made more errors to palm view stimuli ($p<0.05$) and to hand stimuli corresponding to the less-affected hand ($p<0.05$). In addition, they showed a trend towards a rotation*hand interaction effect, indicating more errors for laterally rotated hand stimuli than for medially rotated hand stimuli, but

only when stimuli depicted the less-affected hand ($p<0.1$). See Table I for F(df), p, and η^2 values, and Figure 3 for the percentages of errors.

For response times, several previously reported reaction time effects were present despite the 1700ms delayed response interval. Reaction times showed a main effect of view and a view*rotation interaction. Post hoc tests per view indicated that reaction times for outward rotated stimuli were slower than reaction times for inward rotated stimuli, but only for palm view stimuli ($p<0.05$) and only in the group with typical development. See Table II for F (df), p, and η^2 values, and Figure 4 for the percentages of

Table I: Statistics error analyses

Errors	F(df)	p	η²
Group	(1,18)=8.92	0.01	0.33
View	(1,18)=14.28	0.001	0.44
Group*Hand	(1,18)=5.63	0.029	0.24
Group*View	(1,18)=4.73	0.043	0.21
Nonparametric		**Exact p**	**z**
Group	U=11.0	0.004	−2.77
View		0.005	−2.68

Table II: Statistics response times

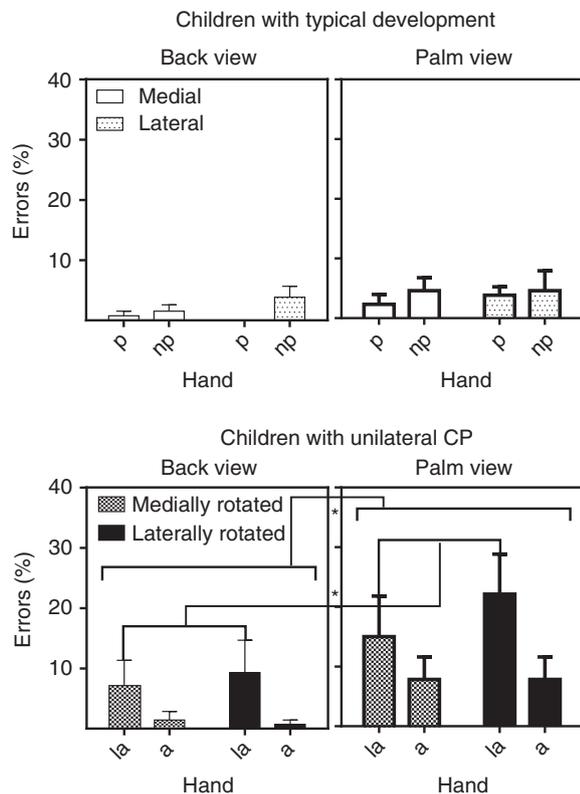| Reaction times	F(df)	p	η²
View	(1,18)=13.57	0.002	0.43
View*Rotation	(1,18)=6.39	0.021	0.26

Figure 3: Error analyses. The upper panels show the bar graphs of the percentage of errors for the group of children with typical development depicted by light shaded bars. Medially rotated stimuli are depicted with white bars, whereas laterally rotated stimuli are depicted by dotted bars. Back view stimuli are depicted with light lined bars whereas palm view stimuli are depicted by bold lined bars. The percentages are depicted for the preferred (p) and non-preferred (np) hand. Asterisks mark the significances (p<0.05). The lower panels show the bar graphs of the percentage of errors for the group with cerebral palsy (CP) depicted by dark shaded bars. Medially rotated stimuli are depicted with patterned bars whereas laterally rotated stimuli are depicted by black bars. Back view stimuli are depicted with light lined bars whereas palm view stimuli are depicted by bold lined bars. The percentages are depicted for the less-affected (la) and affected (a) hand. Asterisks mark the significances (p<0.05).

errors. An overview of the complete statistical results of the behavioural data can be found in Table SI (online supporting information).
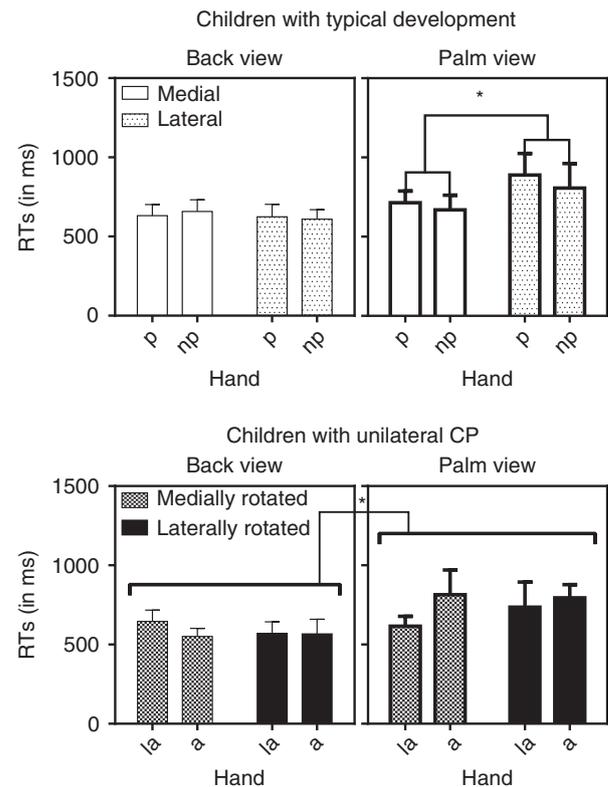

Figure 4: Response time analyses. The upper panels show the bar graphs of the reaction times for the group of children with typical development depicted by light shaded bars. Medially rotated stimuli are depicted with white bars, whereas laterally rotated stimuli are depicted by dotted bars. Back view stimuli are depicted with light lined bars whereas palm view stimuli are depicted by bold lined bars. The percentages are depicted for the preferred (p) and non-preferred (np) hand. Asterisks mark the significances (p<0.05). The lower panels show the bar graphs of the reaction times for the group with cerebral palsy (CP). Back view stimuli are depicted with light lined bars whereas palm view stimuli are depicted by bold lined bars. The percentages are depicted for the less-affected (la) and affected (a) hand. Asterisks mark the significances (p<0.05).

With respect to the ERPs, the N1, P2, and RRN were further analysed. For the N1 component, a hand*view interaction and a group*hand*rotation electrode interaction were observed. Post hoc analyses per group and view revealed a rotation*electrode effect for palm view stimuli (p<0.05) within the group with typical development. That is, the N1 was increased for outward rotated hand stimuli, especially over the contralateral electrode. In the group with CP, no effects were observed on the N1 component.

A main electrode effect was observed for the P2 component with maximal values over Fz. In addition, several interactions with group were found: a group*electrode interaction, a group*hand*view interaction, and a group*hand*view*rotation interaction. However, post hoc analyses only showed some minor electrode effects for back view stimuli in both groups suggesting higher amplitudes over the midline electrode. Bar graphs of the N1 and P2 component amplitudes can be found in Figure S1 and S2 (online supporting information).

RRN demonstrated a main rotation effect which reflected an increased RRN for outward rotated stimuli compared with inward rotated stimuli. In addition, several interaction effects with rotation were found: a hand*rotation interaction, a group*hand*rotation interaction, and a group*hand*view*rotation interaction. For electrode, a group*electrode interaction and a hand*electrode interaction were observed. Post hoc analyses per group revealed a main effect of rotation direction ($p<0.05$) within the group with typical development, confirming more pronounced RRNs for outward rotated hand stimuli than for inward rotated hand stimuli. In the group with CP, a hand*rotation ($p<0.05$) and a hand*electrode interaction were observed ($p<0.05$). Post hoc comparisons indicated a clear rotation effect for the less-affected, but not for the affected hand, again with more pronounced RRNs for outward rotated hand stimuli than for inward rotated hand stimuli (Fig. S3). See Table III for F(df), p, and η^2 values, and Tables IV and V for the ERP component amplitudes (means and SDs). An overview of the complete statistical results of the ERP data can be found in Table SII (online supporting information).

DISCUSSION

In the present study, we investigated the implicit motor imagery ability of children with unilateral CP compared with children with typical development. To study implicit motor imagery capacity, an adapted version of the HLJ task[11] was used to capture ERPs together with overt measures of speed and accuracy. Our main aim was to determine if children with unilateral CP are capable of engaging in an implicit motor imagery task, and if so, if implicit motor imagery capacity would depend on whether the affected hand or the unaffected hand was involved in this task. This issue has, to our knowledge, not been addressed before.

We hypothesized that the group of children with typical development would demonstrate an increase in errors

Table III: Statistics event-related potentials components

	F(df)	p	η^2
N1			
Hand*View	(1,18)=4.44	0.049	0.20
Group*Hand*Rotation*Electrode	(2,17)=4.88	0.029	0.37
P2			
Electrode	(2,17)=22.20	<0.001	0.72
Group*Electrode	(2,17)=3.99	0.038	0.32
Group*Hand*View	(1,18)=6.77	0.018	0.27
Group*Hand*View*Rotation	(1,18)=5.40	0.032	0.23
RRN			
Rotation	(1,18)=6.43	0.021	0.26
Hand*Rotation	(1,18)=11.01	0.004	0.38
Group*Hand*Rotation	(1,18)=5.93	0.026	0.25
Group*Hand*View*Rotation	(1,18)=5.52	0.030	0.24

RRN, rotation-related negativity.

Table IV: Event-related potentials component amplitudes: means (SDs), group of children with typical development

	Left outward	Left inward	Right inward	Right outward
N1 back view				
$F_{contralateral}$	−1.6 (3.81)	−3.4 (3.96)	−4.4 (5.83)	−2.5 (3.40)
$F_{midline}$	−3.6 (3.60)	−4.9 (5.54)	−3.6 (4.45)	−1.1 (3.85)
$F_{ipsilateral}$	−3.1 (2.19)	−3.9 (5.60)	−2.8 (4.21)	−1.0 (4.53)
N1 palm view				
$F_{contralateral}$	−2.0 (3.44)	−6.1 (4.25)	−1.7 (2.84)	−3.3 (4.15)
$F_{midline}$	−3.6 (4.37)	−3.1 (3.68)	−6.2 (3.98)	−1.8 (3.91)
$F_{ipsilateral}$	−3.5 (4.68)	−4.0 (3.26)	−6.0 (3.92)	−1.4 (3.21)
P2 back view				
$F_{contralateral}$	5.5 (4.37)	6.4 (6.72)	5.6 (3.77)	4.0 (6.10)
$F_{midline}$	6.6 (4.66)	6.9 (6.71)	7.2 (4.92)	5.0 (5.78)
$F_{ipsilateral}$	5.1 (3.35)	6.5 (6.50)	6.1 (4.60)	3.8 (6.48)
P2 palm view				
$F_{contralateral}$	7.8 (4.23)	5.8 (4.88)	5.2 (8.65)	7.7 (4.08)
$F_{midline}$	8.3 (3.66)	6.3 (5.64)	6.5 (7.73)	8.5 (4.65)
$F_{ipsilateral}$	6.8 (3.03)	4.8 (5.22)	5.4 (7.18)	7.1 (3.20)
RRN back view				
$F_{contralateral}$	1.1 (6.08)	3.1 (4.38)	1.6 (4.07)	−1.3 (4.90)
$F_{midline}$	−0.7 (4.69)	−0.1 (3.51)	0.3 (5.13)	1.4 (6.03)
$F_{ipsilateral}$	−2.4 (8.23)	−1.6 (4.55)	0.5 (3.85)	−2.0 (6.38)
RRN palm view				
$F_{contralateral}$	−0.7 (4.30)	−0.1 (6.05)	−1.0 (5.46)	−2.00 (5.21)
$F_{midline}$	−2.3 (4.85)	0.2 (4.27)	1.5 (4.27)	−0.6 (5.31)
$F_{ipsilateral}$	−2.7 (3.65)	−2.0 (3.77)	−1.5 (5.47)	−2.4 (4.99)

Table V: Event-related potentials component amplitudes: means (SDs), group of children with cerebral palsy

	Left outward	Left inward	Right inward	Right outward
N1 back view				
$F_{contralateral}$	−0.8 (7.98)	−4.5 (4.36)	−1.9 (10.09)	−3.8 (7.96)
$F_{midline}$	−2.4 (4.02)	−0.9 (7.25)	−1.4 (7.44)	−0.8 (6.39)
$F_{ipsilateral}$	−3.0 (5.33)	−3.3 (3.47)	−1.8 (10.11)	−2.9 (6.32)
N1 palm view				
$F_{contralateral}$	−11.9 (14.85)	0.3 (11.70)	−6.9 (9.13)	−2.9 (6.54)
$F_{midline}$	−1.0 (8.78)	−1.1 (11.43)	2.7 (14.02)	−7.8 (8.50)
$F_{ipsilateral}$	1.6 (12.08)	0.1 (9.52)	−0.5 (10.24)	−7.5 (7.75)
P2 back view				
$F_{contralateral}$	4.6 (4.02)	3.5 (11.13)	1.7 (7.40)	6.5 (7.90)
$F_{midline}$	7.2 (4.45)	2.6 (11.73)	4.5 (7.14)	10.1 (9.01)
$F_{ipsilateral}$	4.1 (6.63)	0.3 (9.70)	2.0 (6.31)	6.3 (8.67)
P2 palm view				
$F_{contralateral}$	9.7 (6.57)	2.3 (5.89)	2.3 (4.63)	−5.1 (17.37)
$F_{midline}$	12.5 (9.41)	7.3 (11.81)	6.3 (5.55)	2.7 (5.22)
$F_{ipsilateral}$	9.3 (8.75)	4.2 (10.19)	3.0 (1.87)	2.5 (4.43)
RRN back view				
$F_{contralateral}$	−2.8 (11.32)	1.4 (8.36)	5.2 (5.45)	2.9 (8.06)
$F_{midline}$	1.7 (13.35)	5.3 (5.61)	2.1 (4.40)	−2.6 (13.66)
$F_{ipsilateral}$	−2.3 (10.46)	1.5 (5.13)	2.0 (9.95)	0.9 (9.94)
RRN palm view				
$F_{contralateral}$	−5.1 (16.62)	8.7 (8.26)	13.0 (8.22)	−1.5 (14.25)
$F_{midline}$	2.6 (8.61)	5.6 (17.36)	−0.4 (17.68)0	−2.8 (12.02)
$F_{ipsilateral}$	−1.3 (11.31)	−0.8 (17.04)	8.8 (10.86)	−2.7 (20.90)

and/or response times together with more marked ERP components in reaction to outward rotated hand stimuli as compared with inward rotated hand stimuli.[10–12] Indeed, children with typical development showed these expected effects with respect to the response times, the N1 component, and RRN, suggesting the use of an implicit motor imagery strategy to solve this task. However, in the group of children with unilateral CP these effects were only observed when depicted stimuli were associated with the less-affected hand. Thus, children with unilateral CP seem capable of engaging in implicit motor imagery, but less so when the affected hand is the subject of the imagery task.

Children with unilateral CP appeared to be less accurate than children with typical development as evidenced by inflated error rates. Of note, within the current study, all children with typical development were able to perform the HLJ task above chance level. Within the group of children with unilateral CP, however, three participants performed at chance level, and were removed from further analyses. For the remaining participants, the group with unilateral CP made significantly more errors than the group of children with typical development, and especially with respect to palm view stimuli. This accords with previous studies that reported diminished implicit motor imagery capacity in children and adolescents with CP.[5,7,13] Interestingly, children with unilateral CP made fewer errors when the presented hand picture corresponded with their affected hand. A similar effect has been described in stroke patients[6] and is known as an hemiplegic advantage.[18] Such an advantage might arise when a different strategy is adapted.[6] With implicit motor imagery tasks, like the HLJ, participants may apply alternative strategies to reach a solution, for example, visual imagery or a third person motor imagery perspective approach may be used instead.[6] It has been proposed that when alternative strategies are used, task performance should be less affected than when a first-person kinematic approach is adapted.[6] This is in line with our observation that children with CP seemed to be less erroneous when the affected limb was involved.

Although we employed a delayed response task, previously reported reaction time effects still could be observed. No group differences on reaction times were observed suggesting that reaction times were predominantly determined by the difficulty of the task rather than general motor speed, in which case the children with unilateral CP should have displayed prolonged reaction times. For both groups, longer reaction times were observed for palm view stimuli than for back view stimuli. Because of the diminished visual familiarity with viewing one's own hands from a palm view perspective, it has been proposed that participants are more likely to engage in motor imagery when palm view stimuli are presented.[11,12]

As expected, with respect to palm view stimuli, children with typical development revealed prolonged reaction times for outward compared with inward rotated stimuli. This commonly reported observation has previously been explained in terms of biomechanical constraints.[9–12] In the group of children with unilateral CP, this reaction time effect was observed only when stimuli depicted the less-affected hand, but not when the affected hand was depicted, suggesting a diminished motor imagery capacity when the affected hand was involved.

With respect to the ERPs elicited by the hand pictures, an N1, a P2, and the classically reported RRN between 350ms and 400ms after stimulus presentation could be observed. Unexpectedly, but in line with the reaction time results, children with typical development had a more marked N1 to outward rotated stimuli compared with inward rotated stimuli for palm view stimuli. This may reflect an increased spatial attention and possibly an early activation of the contralateral located pre-motor areas.[16] In addition, children with typical development had a more marked RRN to outward rotated stimuli compared with inward rotated stimuli. This is in line with previous ERP research applying the HLJ task[10–12] and suggests the use of a first-person kinematic approach to solve this task.[6]

Importantly, within the group of children with unilateral CP, no rotation effect was observed on the ERP N1. In addition, the RRN effect for outward compared with inward rotated hand stimuli was observed only for stimuli depicting the less-affected hand but not for stimuli depicting the affected hand. Together with the reaction time results, these findings suggest that children with unilateral CP are capable of using a first-person kinematic approach to solve the HLJ task when the less-affected hand is involved, but not when the affected hand is involved. Previous studies have suggested that implicit motor imagery depends (in part) on the imagers' body scheme.[7,8] For example, it has been reported that hemiplegic post-stroke participants rely on visual strategies to compensate deficient access to their body schema.[7,8] Although previous research has reported a diminished motor imagery capacity in general in both children and adolescents with CP and children with developmental coordination disorder,[21,22] the current study is the first study, to our knowledge, that reveals a hand-specific decrease in motor imagery capacity. Therefore, motor imagery might be even more intertwined to internal body schema than previously assumed.

Finally, it has been reported that children and adolescents with CP devote a lot of visual attention to their affected limb.[23] For example, Steenbergen et al.[23] reported that during bimanual actions visual attention seemed to be drawn to the affected side of the body in participants with unilateral CP. Others have demonstrated that for the on-line representation of the body schema, both proprioception and visual information are integrated.[7] By covering the hands, as is customary during the HLJ task, our group of children with CP could not fall back on a visual control approach when solving the HLJ task and are proposed to have reduced proprioceptive input from the affected hand resulting in diminished performance when the affected hand was involved.

In conclusion, we found that children with unilateral CP were able to engage in a first-person kinematic approach to solve the HLJ task with respect to their less-affected hand. However, with respect to the affected hand these children seemed to rely on a visual rotation strategy to solve the task, suggesting diminished proprioception and less access to the body schema in children with unilateral CP when the affected hand is involved. This suggests that children with CP could benefit from intervention based on visual training strategies.

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SUPPORTING INFORMATION

The following additional material may be found online:

Figure S1: N1 amplitude results of the group of (a) children with typical development and (b) children with unilateral cerebral palsy.

Figure S2: P2 amplitude results of the group of (a) children with typical development and (b) children with unilateral cerebral palsy.

Figure S3: Rotation-related negativity (RRN) results of (a) children with typical development (TD) and (b) children with unilateral cerebral palsy.

Table SI: Statistical results of the behavioural data: (a) error analyses and (b) response times.

Table SII: Overview statistical results of the ERP component amplitudes.

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