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Explicit and implicit motor learning in children with unilateral cerebral palsy

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ABSTRACT

Objectives: The current study aimed to investigate the capacity for explicit and implicit learning in children with unilateral cerebral palsy.

Participants: Children with left and right unilateral cerebral palsy and typically developing children shuffled disks toward a target.

Design: A prism-adaptation design was implemented, consisting of pre-exposure, prism exposure, and post-exposure phases. Half of the participants were instructed about the function of the prism glasses, while the other half were not.

Measures: For each trial, the distance between the target and the shuffled disk was determined. Explicit learning was indicated by the rate of adaptation during the prism exposure phase, whereas implicit learning was indicated by the magnitude of the negative after-effect at the start of the post-exposure phase.

Results No significant effects were revealed between typically developing participants and participants with unilateral cerebral palsy. Comparison of participants with left and right unilateral cerebral palsy demonstrated that participants with right unilateral cerebral palsy had a significantly lower rate of adaptation than participants with left unilateral cerebral palsy, but only when no instructions were provided. The magnitude of the negative after-effects did not differ significantly between participants with right and left unilateral cerebral palsy.

Conclusions: The capacity for explicit motor learning is reduced among individuals with right unilateral cerebral palsy when accumulation of declarative knowledge is unguided (i.e., discovery learning). In contrast, the capacity for implicit learning appears to remain intact among individuals with left as well as right unilateral cerebral palsy.

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➤ IMPLICATIONS FOR REHABILITATION

- Implicit motor learning interventions are recommended for individuals with cerebral palsy, particularly for individuals with right unilateral cerebral palsy
- Explicit motor learning interventions for individual with cerebral palsy – if used – best consist of singular verbal instruction.

Introduction

Cerebral palsy (CP) is defined as a "group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbance of the brain that occurred in the developing fetal or infant brain. The motor disorders are often accompanied by disturbances in sensation, perception, cognition, communication, and behavior, by epilepsy and by secondary musculoskeletal problems" [1, p. 9]. A conspicuous characteristic of CP is that it is a heterogeneous condition not only in terms of its etiology but also with respect to the type and severity of disorders that accompany CP. Put simply, there is very high variability in motor performance among individuals with CP.

Here, we address differences among children with left and right unilateral CP. In unilateral CP or hemiplegic CP, movement of one side of the body is limited [2], although the opposite side of the body may also be affected to some extent [3]. Individuals with left and right unilateral CP (i.e., with right and left hemisphere disturbances, respectively) show clear differences in their ability to use appropriate grip patterns when picking up objects, particularly if grasping the object is subordinate to a more important goal. Steenbergen et al. [4], for example, observed that when grasping pencils to mark a dot on a sheet of paper, adolescents with right unilateral CP frequently used a grip that was comfortable for picking up the pencil, but not suitable for the primary purpose of marking the dot. However, young individuals with left unilateral CP were much more likely to select a grip that was optimal for marking the dot, even when this meant first grasping the pencil in an awkward manner. Ensuing studies have generally confirmed that individuals with right unilateral CP tend

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to be less capable of deliberate or conscious planning in the production of motor actions [5–8], although some have contested this [9].

In general, research on motor *learning* in children with CP does not consider individual differences [10,11]. Nonetheless, individual differences warrant further study, so that tailor-made rehabilitation (and sport participation) programs can be developed and individualized treatment is advanced. Accordingly, the present study aimed to investigate differences in the capacity for explicit and implicit motor learning among children with left and right unilateral CP.

The key difference between explicit and implicit motor learning is conscious engagement in movement production during practice, and the concomitant accumulation of verbal or declarative task-relevant knowledge during the early stages of learning to produce a movement [12–16]. An explicit learner deliberately generates and tests hypotheses about how to produce the appropriate movements, which typically results in increased verbal task-relevant knowledge. Therapists (or coaches) can facilitate explicit learning by providing instructions and feedback about the desired movement form; yet, instructions and feedback are not compulsory for explicit learning to occur. Learners can also actively search to acquire task-relevant knowledge on their own. This is called discovery learning [12]. Active search, such as testing hypotheses about the appropriate movement form, is underpinned by working memory [17]. Therefore, working memory supports explicit learning by retaining, recalling, and manipulating task-relevant information over short periods of time [18]. In particular, the verbal component of working memory is pertinent for explicit learning [19,20]. Overloading verbal working memory, by, for instance, performing a concurrent verbal task while the motor activity is practiced, significantly disrupts explicit learning. In fact, researchers have often resorted to secondary tasks to induce implicit motor learning because dual tasking prevents a learner from accumulating declarative knowledge [12]. Implicit motor learning is the counterpart of explicit learning, and is thought to occur without active accumulation of declarative knowledge [12,13], and is sometimes considered as unintentional [21]. Repeated exposure (e.g., practice) instead results in the immediate development of procedural or rule-based knowledge about how a movement is performed, which cannot be expressed explicitly.

Behavioral differences in explicit and implicit learning are also recognizable in patterns of cortical activation. For instance, evidence suggests that explicit motor learning is more strongly associated with left hemisphere activity than implicit motor learning, particularly in regions of the left temporal cortex [22,23] and the left dorsolateral prefrontal cortex [24–26]. The left dorsolateral prefrontal cortex has also been shown to be involved in verbal working memory tasks [27–29].

The interrelatedness of explicit motor learning and left hemispheric activity, together with the reduced ability for explicit or conscious control of motor actions in individuals with right unilateral CP [e.g., 4], raises questions about the capacity for explicit motor learning in CP, especially in individuals with right unilateral CP. It is relevant in this regard that children with CP do show reduced working memory ability compared to typically developing children [30–32]. Moreover, Gagliardi et al. [10,11] reported that 40% of children with CP who showed poor working memory ability failed to learn a sequential learning task (i.e., Corsi Span test). However, Gagliardi et al. [10,11] acknowledged that learning on the Corsi Span test most likely reflects a blend of explicit and implicit learning. It is therefore unclear from such studies whether motor learning impairments in CP can, or cannot, be attributed to explicit learning that is disrupted by reduced working memory ability. Such studies also reveal little about the consequences of disturbances in the left hemisphere.

One method to distinguish an individual's capacity for explicit and implicit learning is the prism-paradigm [16,33]. Donning glasses with prism lenses displaces the visual field to the left or right side, and thus alters the mapping between vision and proprioception. Consequently, individuals wearing glasses with prism lenses make systematic spatial errors when pointing or throwing towards a target [34,35]. Adaptation to the prism lenses is a function of explicit learning. That is, individuals monitor their errors and actively form hypotheses to increase the accuracy of their movements (i.e., pointing or throwing). The verbal task-relevant knowledge that is discovered during this process of explicit learning can also be obtained from instructions, which often results in a faster rate of adaptation. In parallel, however, individuals also re-adjust the mapping between their vision and proprioception, which occurs implicitly with little conscious awareness [16]. Thus, increasingly accurate pointing or throwing during prism exposure reflects the contributions of both explicit and implicit motor learning. Nevertheless, a faster rate of adaptation is generally attributed to explicit learning [16,36]. Indeed, Redding, Rader, and Lucas [37] showed that rate of adaptation during prism exposure was reduced when participants' ability to learn explicitly was disrupted by cognitively loading working memory.

After the glasses with prism lenses are removed, pointing or throwing is typically aimed to the side opposite to the prism displacement, which is called a negative after-effect. Individuals presumably are unaware that the mapping between vision and proprioception has re-adjusted during adaptation, so negative after-effects are considered a pure measure of the implicit learning that took place during the exposure to the prisms, that is, during adaptation [16,36]. This is consistent with observations that loading working memory cognitively during prism exposure does not affect the magnitude of the after-effects [37].

The main purpose of the current study was to explore the capacity for explicit and implicit motor learning in children with CP, and to examine differences associated with left and right unilateral CP. To this end, children with and without unilateral CP performed a far aiming task during which they had to slide or shuffle small disks to a target (as in shuffle boarding, a traditional Dutch sport). After an initial bout of 40 trials (i.e., pre-exposure phase), the participants shuffled 40 disks while exposed to glasses with prism lenses (i.e., prism exposure phase) and another 40 disks after removal of the glasses with prisms (i.e., post-exposure phase). Half of the participants were left naïve to the effects of the prism lenses (i.e., the no-instruction group); they did not receive any explanation regarding the prism lenses and were left to their own devices to discover how to shuffle the disks accurately. The other half of the participants were informed of the visual field displacement induced by the prism lenses and received instructions how to compensate for the displacement when shuffling the disks (i.e., instruction group).

Differences in the rate of adaptation after donning the glasses with prism lenses were used as a measure of explicit learning, while differences in the magnitude of the negative after-effect once the glasses with prisms were removed were used as a measure of implicit learning [16,35]. Because individuals with CP tend to have poor working memory ability, we anticipated weaker explicit learning than in typically developing peers, reflected by a slower rate of adaptation to the prisms. Further, because individuals with right unilateral CP tend to be less capable of more deliberate, conscious aspects of movement than individuals with left unilateral CP, we anticipated that disrupted explicit learning would be more evident in individuals with right unilateral CP. In contrast, since implicit learning is independent of conscious control and working memory, we anticipated similar implicit learning across groups, reflected by negative after-effects of the same order of magnitude. Finally, consideration of the rates of adaptation for the no-instruction and instruction groups, allowed us to explore to what degree explicit learning by typically developing children or children with UCP depends on verbal instructions or whether it can also proceed unguided via discovery learning.

Method

Participants

Thirty-one young individuals with unilateral CP volunteered. All participants attended schools for special education. Because we had no access to medical files, the diagnosis and classification of unilateral CP was confirmed by either the physical therapist, the physical education teacher and/or parents.[1] The reported GMFCS levels were between I and III. The Box & Blocks Test was administered to assess gross manual dexterity of the affected and the less affected hand [38]. The Box & Blocks is increasingly used to assess children and young adults with unilateral CP [39]. It requires participants to move as many small cubes (2.5 cm) as possible from one compartment of a box (53.7 × 25.4 × 8.5 cm) to the other in 60 s. Both hands are tested, starting with the less affected hand. The ICC for test–retest and inter-observer reliability of the Box & Blocks are reported to be 0.85 and 0.99, respectively [38,39]. For inclusion, participants had to be able to understand the instructions and respond verbally to questions from the experimenters. They also needed to be able to point directly to the target, and to be able to slide (i.e., shuffle) the disks with their preferred hand.

Four volunteers were excluded from participation because they were incapable of performing the disk sliding action. This yielded 27 participants with CP of whom 12 had left unilateral CP (3 girls; *M* age = 15.9 years, SD = 1.9; *M* left hand Box & Blocks Test = 15.9, SD = 6.8; *M* right hand Box & Blocks Test = 19.9, SD = 5.7) and 15 had right UCP (7 girls, *M* age = 15.1 years, SD = 2.3; *M* left hand Box & Blocks Test = 19.5, SD = 4.5; *M* right hand Box & Blocks Test = 8.7, SD = 6.6). An additional 18 typically developing self-proclaimed right-handed adolescents formed an age-matched reference group (10 girls; *M* age = 14.0 years, SD = 1.8). The typically developing children were recruited from regular schools. Participants had normal or corrected to normal vision. All participants and parents gave written informed consent. The research procedures were ratified by the local Ethics Review Committee and followed the principles of the Declaration of Helsinki.

Apparatus and material

The shuffleboard was custom-made from white medium density fiberboard (MDF) and measured 165 cm in length and 105 cm in width and placed on a table. A white wood-strip (2 cm in height) was placed along the two side edges in order to prevent the disk from falling off the board. A wood-strip attached to the far end of the shuffleboard was divided at its midpoint by a black vertical marker (0.5 cm in width), which served as the target. The disks were wooden checker stones of 3.5 cm diameter. A Casio EX-F1 High Speed camera (Casio Europe GmbH) was placed directly above the target. A white cloth at the far end of the shuffleboard prevented the participants from seeing the tripod to which the camera was attached. The frame rate of the pre-calibrated camera was set at 300 fps. Two pairs of identical glasses were used throughout the experiment. 3M™ Press-On™ 15 prism diopters (3M, USA) were applied to both lenses of one of the pairs. From the participant's point of observation (i.e., standing in front of the board at 165 cm), the prism lenses visually shifted the target an estimated 24 cm towards the right.

Procedure and design

The shuffleboard task was modeled on a traditional Dutch sport. The children were required to slide the disk over the board to hit the target at the far end, using their preferred (i.e., less affected) hand. They sat on an adjustable chair when sliding the disk (i.e., to minimize any adverse effects of postural imbalance), with exception of two children with unilateral CP, who remained in their wheelchair. Throughout the experiment, disks were placed in each child's hand in order to prevent the child from reaching for the disk, missing, and then becoming aware of the visual field shift induced by the prisms. Children shuffled one disk at a time, and after every attempt the experimenter removed the disk from the shuffleboard. The children were told to hit the target and were allowed to take as much time as they needed. If the disk did not touch the wood-strip at the far end of the shuffleboard the trial was repeated.

The experiment consisted of three phases: a pre-exposure phase, a prism exposure phase, and a post-exposure phase. In each phase, children performed 40 trials. At the start of each phase, a child donned a pair of glasses, with or without prism lenses (depending on the phase). To make the link between the glasses and the visual field displacement less obvious, the glasses were removed halfway through each phase (i.e., after trials 1 to 20). However, the same glasses were returned for the second set of trials in the phase (i.e., trials 21 to 40), unbeknownst to the children. At the start of the experiment, the children were allowed five familiarization trials, after which they donned the glasses without the prisms and performed 40 shuffles (i.e., pre-exposure phase). They then donned the glasses with prism lenses and performed another 40 trials (prism exposure phase), after which the glasses were changed and a further 40 trials were completed without prisms (post-exposure phase). This completed the experiment.

The children were randomly assigned to either the no-instruction or the instruction group. That is, nine typically developing children were assigned to the no-instruction and instruction groups, and nine and six children with right unilateral CP were assigned to the no-instruction and instruction groups, respectively. The no-instruction and instruction groups of children with left unilateral CP consisted of six participants each. The no-instruction groups were not told that glasses with prism lenses would be used, and were also not instructed how to overcome the bias induced by the visual field displacement. Consequently, to maintain or improve shuffling performance they were fully dependent on their own monitoring of where the disk landed relative to the target (i.e., unguided discovery learning). In contrast, the instruction groups were told before the pre-exposure phase that they would be wearing special glasses with prism lenses. It was explained to them (both verbally and using schematic drawings) that the prism lenses would shift the visual field to the right, and that large shuffling errors would occur if they did not take this into account. They were also instructed that to prevent these errors from occurring they should aim to the left of the target (i.e., approximately 24 cm). To make sure the children understood the instructions, they were asked to repeat them in their own words. After performing the pre-exposure phase, immediately before the start of the prism exposure phase, the children were briefly reminded of the instructions.

Data extraction and analysis

The high-speed recordings were digitized and processed using WinAnalyze (Mikromak Service Brinkmann, Germany) and Matlab_R2014b (Mathworks, USA) to provide for each trial the horizontal distance (in mm) between the midpoint of the disk and the target at the moment the disk contacted the wood-strip at the far end of the shuffleboard. Positive and negative values indicate an error to the right or left of the target, respectively. To assess explicit learning, the rate of adaptation to the prism lenses was determined by calculating the average shuffling bias to the right for the first four sets of three trials of the prism exposure phase. Thus, to provide the shuffling bias, the average shuffling error of the final three trials in the pre-exposure phase was subtracted from the average shuffling error of the first (i.e., trials 1 to 3), second (i.e., trials 4 to 6), third (i.e., trials 7 to 9), and fourth (i.e., trials 10 to 12) set of three trials in the prism exposure phase. Adaptation was considered complete if the bias did not exceed zero. To assess implicit learning, the magnitude of the negative after-effect was determined by calculating the average shuffling bias to the left in the first set of three trials of the post-exposure phase. That is, the average shuffling error of the final set of three trials in the pre-exposure phase was subtracted from the average shuffling error of the first set of three trials in the post-exposure phase.

Because of the small number of participants, within groups non-parametric tests were used to explore differences in rate of adaptation and after-effects. That is, Wilcoxon Signed-ranks tests were used to evaluate whether shuffling biases for the different sets of trials were significant (i.e., whether the shuffling error for the different sets of trials in the prism exposure and post-exposure phases were significantly higher and lower than the shuffling error in the final set of trials in the pre-exposure phase). Mann–Whitney tests were used to examine if shuffling bias in the prism exposure phase was higher in children with unilateral CP than in typically developing children, and in children with right unilateral CP than in children with left unilateral CP. Mann–Whitney tests were also used to evaluate whether shuffling bias in the post-exposure phase differed between the groups. Bonferonni adjustments to the α-values were made to reduce the chance of Type I errors. For the Mann–Whitney tests, the *z*-values were used to calculate effect size *r* with a large effect being 0.5 or higher [40].

Results

Perusal of Figures 1 to 4 shows that the instructions were effective. After donning the prisms, the no-instruction groups initially made significant rightward shuffling errors before adapting. In contrast, adaptation in the instruction groups was almost immediate, even resulting in slight overcompensation toward the left. All groups, however, demonstrated clear after-effects when the prisms were removed, irrespective of whether they received instruction or not. In the following, we first address the differences in adaptation and after-effects for the no-instruction groups and then for the instruction groups.

Adaptation in the no-instruction groups

For each group, Wilcoxon Signed-ranks tests (one-tailed, $\alpha = 0.0125$) were performed to assess whether shuffling bias (i.e., the average error during the prism exposure phase compared to the average error in the final three trials in the pre-exposure phase) was significantly to the right. A more enduring rightward bias reflects slower adaptation, and hence weaker explicit learning (Willingham, 1998). The typically developing children displayed significant rightward shuffling bias in prism exposure trials 1–3, $W(9) = 43$, $p = 0.005$, but not in trials 4–6, 7–9, and 10–12, W's ≤ 29, p's ≥ 0.05 (Figure 1). Similarly, children with left unilateral CP displayed a significant rightward bias in trials 1–3, $W(6) = 21$, $p < 0.025$[2], but not in the later trials, W's ≤ 7, p's ≥ 0.05. In contrast, the rightward shuffling bias for the children with right

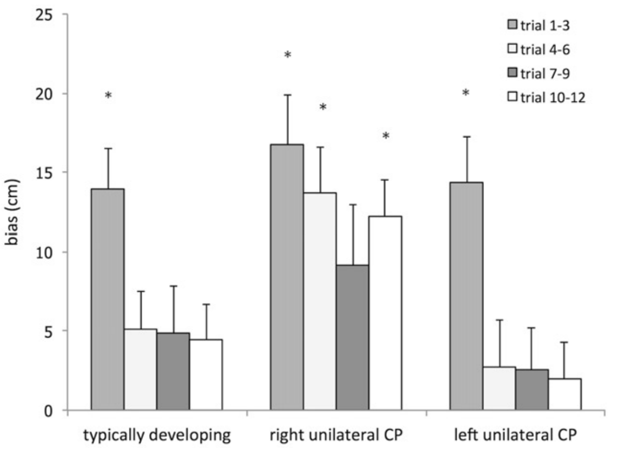

Figure 1. Shuffling bias (means and standard errors) during the first 12 trials of the prism exposure phase in the no-instruction groups ('*' indicates that the bias significantly exceeds zero).

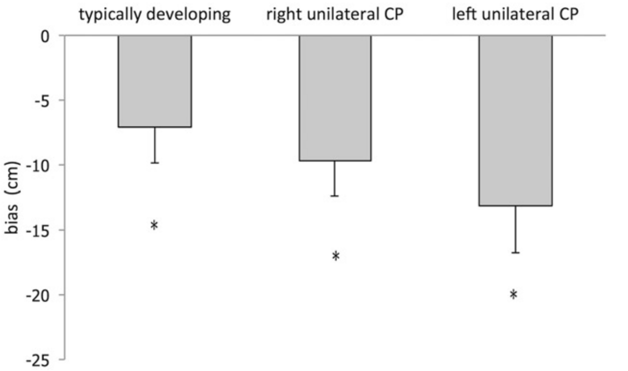

Figure 2. Shuffling bias (means and standard errors) during the first three trials of the post-prism exposure phase in the no-instruction groups ('*' indicates that the bias significantly exceeds zero).

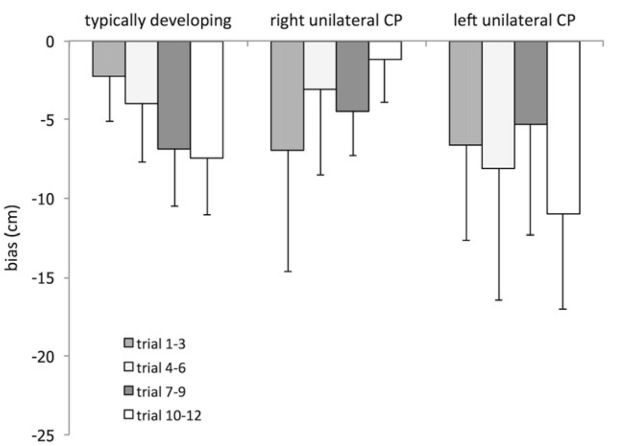

Figure 3. Shuffling bias (means and standard errors) during the first 12 trials of the prism exposure phase in the instruction groups.

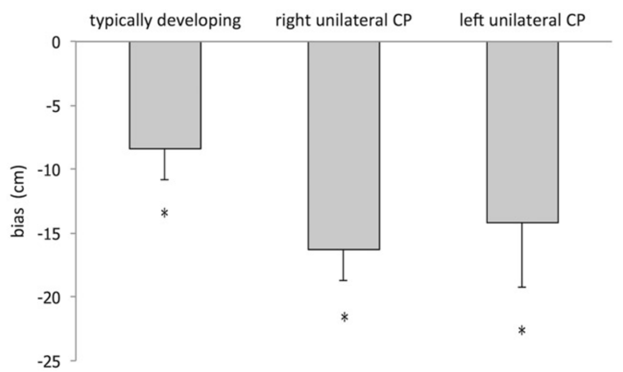

Figure 4. Shuffling bias (means and standard errors) during the first three trials of the post-prism exposure phase in the instruction groups ('*' indicates that bias significantly exceeds zero).

unilateral CP was more enduring. Wilcoxon Signed-ranks tests indicated significant biases for prism exposure trials 1–3, 4–6, and 10–12, W's = 45, p's = 0.005, but not for trials 7–9, $W(9) = 35$, $p = 0.025$ (Figure 1).

To evaluate whether children with unilateral CP showed a larger rightward shuffling bias than their typically developing peers, Mann–Whitney tests were performed (one-tailed, $\alpha = 0.0125$). Greater shuffling bias reflects less adaptation and hence weaker explicit learning. No significant differences between the two groups occurred for prism exposure trials 1–3 through 10–12, U's ≥ 48, p's ≥ 0.13, r's ≤ 0.23. Finally, the conjecture that children with right unilateral CP would have greater shuffling bias to the right than children with left unilateral CP was investigated. Mann–Whitney tests (one-tailed, $\alpha = 0.0125$) showed that the rightward bias in prism exposure trials 4–6 and 10–12 was indeed significantly greater, with large effect sizes for the children with right UCP, U's ≤ 7, p's ≤ 0.010, r's ≥ 0.59, but rightward bias was not significantly greater during trials 1–3 and 7–9, U's ≥ 16, p's ≥ 0.10, r's ≤ 0.32 (Figure 1).

After-effects in the no-instruction groups

Wilcoxon Signed-ranks tests (one-tailed, $\alpha = 0.05$) were performed to examine whether, for the no-instruction groups, shuffling bias to the left (i.e., the average error of the first three trials in the post-exposure phase compared to the average error in the final three trials of the pre-exposure phase) was significant. A significant leftward bias reflects a negative after-effect, confirming implicit learning. It was revealed that for each of the three groups leftward shuffling bias was significant after the prisms were removed, W's ≥ 19, p's ≤ 0.037 (Figure 2).

Mann–Whitney tests (two-tailed, $\alpha = 0.05$) were subsequently used to assess whether leftward shuffling bias varied between the groups, which would indicate differences in implicit learning. The leftward bias in typically developing children was not significantly different from the leftward bias in children with unilateral CP, $U = 44$, $p = 0.17$, $r = 0.28$. The leftward biases in children with right and left unilateral CP were not significantly different either, $U = 21$, $p = 0.51$, $r = 0.17$ (Figure 2).

Adaptation in the instruction groups

First, Wilcoxon Signed-rank tests (one-tailed, $\alpha = 0.0125$) were conducted to assess if there were significant shuffling biases to the right. This showed that, with instruction, adaptation was immediate in all groups; that is, none of the groups showed a significant shuffling bias in prism exposure trials 1–3, W's ≤ 15, p's > 0.05, or in any of the subsequent trials, W's ≤ 29, p's ≥ 0.05 (Figure 3). In addition, Mann–Whitney tests (one-tailed, $\alpha = 0.0125$) indicated that there were no significant differences in shuffling bias between the children with UCP and the typically developing children for prism exposure trials 1–3 through 10–12, U's ≥ 45, p's ≥ 0.27, r's ≤ 0.13. Nor were there significant differences in bias between children with right unilateral CP and left unilateral CP, U's ≥ 10, p's ≥ 0.11, r's ≤ 0.35 (Figure 3).

After-effects in the instruction groups

Wilcoxon Signed-ranks tests (one-tailed, $\alpha = 0.05$) were performed to examine whether the groups demonstrated a leftward shuffling bias (i.e., a negative after-effect) in the post-exposure phase, indicating implicit learning. Similarly to the no-instruction groups, all groups displayed a significant bias to the left, W's ≥ 19, p's ≤ 0.037 (Figure 4). Further, Mann-Whitney tests (two-tailed, $\alpha = 0.05$) revealed that the leftward bias in children with unilateral CP was significantly greater with a medium effect size than in typically developing children, $U = 26$, $p = 0.026$, $r = 0.46$. However, comparison of children with right and left unilateral CP revealed no significant differences in the magnitude of their leftward bias, $U = 16.5$, $p = 0.44$, $r = 0.05$ (Figure 4).

Discussion

The current study explored whether the capacity for explicit learning was reduced in children with unilateral CP relative to typically developing children, and particularly in children with right unilateral CP. The rationale for this hypothesis was two-fold. First, explicit learning is thought to be associated with conscious motor processes, such as hypothesis testing about movement, which rely on working memory [13]. Given that children with CP often present poor working memory ability [30,31], reduced explicit learning was anticipated relative to their typically developing peers. Additionally, explicit learning seems to be more associated with left hemisphere activity than implicit learning [23], so given that children with right unilateral CP have poorer conscious control of motor processes [4,6], we expected their capacity for explicit learning to be particularly affected. Moreover, since implicit learning does not depend on conscious processes (e.g., hypothesis testing), and thus makes few demands on working memory, we anticipated similar implicit learning across the groups.

Explicit learning

The hypotheses regarding explicit learning were partly supported. The rate of adaptation to the prisms was not different for the typically developing children compared to children with unilateral CP, irrespective of whether or not they were explicitly instructed about the function of the prisms. In other words, taken as a group, the children with unilateral CP did not show reduced explicit learning. However, strong differences arose within the group of children with unilateral CP. Children with right unilateral CP needed considerably more trials to adapt to the prism lenses than children with left unilateral CP. Children with left unilateral CP needed only three attempts, as did their typically developing peers, but children with right unilateral CP were still not fully adapted to the prism lenses after 12 trials. In other words, children with right unilateral CP clearly demonstrated more trouble learning explicitly.

Importantly, however, poor explicit learning only occurred among children with right unilateral CP who did not receive instructions. Individuals with right unilateral CP who did receive instructions were capable of consciously controlling and monitoring their actions to support learning. Consequently, children with unilateral CP can learn explicitly, but only when instructed exactly what to do. By contrast, if no instructions are provided, then the effectiveness of explicit learning seems considerably reduced among individuals with right unilateral CP. Explicit motor learning without instructions or feedback amounts to what is often called (unguided) discovery learning [12,17,41]. Typically, discovery learning is associated with increases in verbal task relevant knowledge as a consequence of conscious processes, such as hypothesis testing. Hence, the present study suggests that children with right unilateral CP either do not engage in such processes, or, alternatively, engage in hypothesis testing behavior that is unsystematic or unproductive [42]. For example, hypothesis generation may be ineffective if a hypothesis is formulated with too many dimensions, or is too complex to monitor. Additionally, children may be poor at adapting the original hypothesis or in formulating alternatives [43]. Although difficult to use with young children, the adoption of think aloud protocols during practice may prove helpful to uncover the reasons for ineffective hypothesis testing in individuals with right unilateral CP.

Buszard [44] reported that in 6- to 11-year-old children who practiced a basic tennis skill, more hypothesis testing (as indicated by visible alterations in movement execution during practice and verbal recall of hypotheses tested after learning) was associated with larger verbal working memory capacity [45]. Previous work, however, did not find differences in working memory capacity between individuals with right and left unilateral CP [28]. Hence, it is doubtful that problems in hypothesis testing in unilateral CP can be attributed to poor working memory capacity. In any case, it is unlikely that working memory is the only determinant of poor hypothesis testing, or more generally, explicit motor learning [46]. Otherwise, the children with unilateral CP as a group should have shown poor explicit learning, since they normally have poorer working memory ability [30,31]. This was not the case, as children with left unilateral CP adapted as quickly to the prisms as their typically developing peers. It is important that future work on motor learning in individuals with unilateral CP directly assesses working memory ability, taking into account both the verbal and visual-spatial components, and also considers the propensity to consciously process movements, which has been associated with working memory ability and efficiency of explicit motor learning in healthy adults and children [20,47].

These findings have clear implications for treatment of children with UCP in rehabilitation (or in physical education and sports). Explicit learning methods can be useful for promoting motor learning in these children. Nevertheless, children with right unilateral CP depend on explicit instructions or feedback more than children with left unilateral CP, who appear capable of learning without instructions or feedback. Importantly, however, the amount and complexity of the instructions and feedback provided to children with unilateral CP should be minimized to prevent conscious processes from overloading their poor working memory [42].

Implicit learning

The degree of implicit learning during prism exposure is reflected in the magnitude of the negative after-effects in the post-exposure phase, that is, after the prism lenses are removed [13,32]. In our study, significant negative after-effects were revealed in children with and without unilateral CP, and both when they had received instructions about the working of the prisms and when they had not. Hence, poor explicit learning by children with right unilateral CP, which we discussed above, does not expose a *general* incapacity for motor learning [6]. On the contrary, the absence of any differences in negative after-effects among groups of individuals with right and left unilateral CP suggests similar levels of implicit learning. If anything, the larger after-effects imply that implicit learning in individuals with unilateral CP may have been stronger than in the typically developing participants. It is not particularly clear why this would be the case; however, poor working memory ability in individuals with CP [30,31] might place greater emphasis on implicit learning than in typically developing people. In any event, the present findings show that implicit motor learning can be achieved, even if behavioral and neural processes associated with explicit learning are compromised. This further supports the contention that implicit and explicit motor learning are fundamentally different [12,16,48,49].

Consequently, implicit learning interventions, such as analogy instructions [50] or error-minimizing approaches [51], may be particularly advantageous for treatment during rehabilitation or may help to alleviate skill barriers to (continued) sports participation [14,52]. This would be true for children with left unilateral CP as well as right unilateral CP.

Conclusion and limitations

To conclude, the present observations suggest that the capacity for explicit motor learning was reduced in individuals with right unilateral CP but not in individuals with left unilateral CP. The capacity for implicit learning seemed intact in both left and right unilateral CP individuals. However, it is pertinent to further substantiate these interpretations, especially because the current study is limited with respect to its sample size. Perhaps more importantly, we cannot rule out the possibility that baseline differences other than the side of the lesion (e.g., type of insult or extent of the lesion) did modulate learning. Accordingly, it must be recognized that this study is necessarily exploratory. This said, the findings do highlight the prospects for conducting a randomized controlled trial to try to obtain stronger scientific evidence. A final possible limitation is that the present findings are restricted to the less impaired, preferred hand. This may or may not affect the clinical relevance of the study. In many activities, however, individuals with cerebral palsy strive to maximize their motor performance by using their less impaired hand.

Notes

1. We cannot provide neuroimaging data on lesion location, data on birth history or neurological quantification of the degree of asymmetry between the two sides. Consequently, it cannot be ruled out that group differences other than the side of lesion (e.g., extent of lesion, type of insult) that potentially modulate motor learning were present.
2. For $N = 6$, Wilcoxon Signed-ranks tests does not return p values below .025. Since all children with left UCP had a positive shuffling bias, we interpret the bias as statistically relevant, even though $p = .025$ does exceed the corrected α-value of .0125.

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Disclosure statement

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