Motor learning in children with hemiplegic cerebral palsy: feedback effects on skill acquisition

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ABBREVIATION
RMSE Root-mean-square error

AIM Motor learning is enhanced with practice and feedback. This cohort control study investigated the effect of different relative feedback frequencies during skill acquisition in children with cerebral palsy (CP) and children with typical development.

METHOD Nineteen children with spastic hemiplegic CP (nine males, 10 females; mean age 11y 7mo; range 8–16y) and 20 children with typical development (12 males, eight females; mean age 10y 8mo; range 8–14y) were assigned to 100% or reduced (62%) feedback subgroups as they practised 200 trials of a discrete arm movement with specific spatiotemporal parameters. Children with CP used their less involved hand. Learning was inferred by delayed (24h) retention and reacquisition tests.

RESULTS All children improved in accuracy and consistency. Children with typical development demonstrated significantly greater accuracy than children with CP during acquisition (p=0.001), retention (p=0.031), and reacquisition (p=0.001), and greater consistency during retention (p=0.038). The typically developing group who received 100% feedback performed with significantly less error than the 62% feedback group during acquisition (p=0.001), and with greater retention (p=0.017). No statistically significant difference was found between feedback subgroups of children with CP, although the 100% feedback group consistently demonstrated less error.

INTERPRETATION Children with CP use feedback in a manner similar to children with typical development when learning new skills with their less involved hand, but demonstrate less accuracy and consistency.

All children learn new motor skills to increase their independence and participation in daily routines. Children with cerebral palsy (CP) often demonstrate different motor learning strategies owing to sensory, motor execution, and cognitive impairments. It is well documented that augmented feedback provided as individuals practise a motor task enhances their learning and ultimately their skill acquisition. Although therapeutic intervention emphasizes the learning and relearning of motor tasks, little information is available to guide practitioners in the effective use of feedback schedules to enhance acquisition and retention of motor skills in children with CP.

Early motor learning research, carried out by exercise and movement scientists, showed that accuracy and consistency in a delayed retention test is higher among adults who practise motor skills in reduced-feedback conditions than in those who practise with feedback provided during every practice trial. Influenced by these studies, clinicians are incorporating (1) more structured practice conditions and (2) frequency manipulation of extrinsic feedback during intervention sessions. In a landmark study, the effect of augmented feedback on adults with and without unilateral brain damage was examined as they learned a new motor skill. Although adults with unilateral brain damage exhibited more error than control participants as they practised a rapid spatially and temporally constrained task (using their less involved upper extremity), their learning patterns were similar to those demonstrated by participants without unilateral brain damage. Differences between the groups of adults were attributed to motor control and execution, not the cognitive learning of the motor skill.

While adult research provides some insight into how feedback frequency affects motor learning, children have different cognitive processes to those of adults, such as their developing capabilities for information-processing, sustained attention, and memory. The differences between children and adults in the use of feedback have
been investigated during a similar visuomotor skill acquisition task. Unlike adults, who benefited more from reduced feedback (with feedback presented for 62% of trials) as they learned the motor task, children with typical development showed greater accuracy and consistency during acquisition and retention if they practised with feedback provided after each trial (100% feedback). Specifically, when children received reduced feedback, they performed with greater temporal (timing) error. In another study, children with typical development demonstrated greater retention and transfer of skills when learning a complex throwing task if 100% feedback was provided.

To accommodate performers with different abilities, theorists have proposed the Challenge Point Framework, in which motor learning is considered as an interaction of the information-processing capabilities of the learner, the task demands, and practice conditions. Given the same task and practice conditions, it is anticipated that children with hemiplegic CP would require increased cognitive effort or challenge to learn a new motor task. However, it is not known if feedback during practice benefits children with CP in a similar manner to children with typical development. This study investigated the effect of different feedback frequencies during practice on the acquisition and retention of a fast discrete motor skill in children with hemiplegic CP. To minimize the execution-related performance deficits and focus on how the cognitive challenge of reduced feedback affects learning capability in children with CP, we asked the children with hemiplegic CP to practise the motor task using their less involved arm. We hypothesized that, when practising with the less involved arm, children with hemiplegic CP would demonstrate (1) greater error than children with typical development owing to motor execution differences and (2) use augmented feedback in a similar manner to children with typical development, suggesting similar cognitive motor learning abilities during skill acquisition.

**METHOD**

**Participants**

Nineteen children with spastic hemiplegic CP (nine males, 10 females; mean age 11y 7mo, SD 2y 4mo, range 8–16y; Manual Abilities Classification System levels I-III) and 20 children with typical development (12 males, eight females; mean age 10y 8mo, SD 2y, range 8–14y) were recruited from the areas in and surrounding Albuquerque, New Mexico, and Los Angeles between 2006 and 2011. Inclusion criteria for all children were (1) academic performance within 1.5 years of grade-level expectations and (2) demonstrated attention to complete research protocols. Exclusion criteria for all participants were (1) additional orthopaedic or neurological diagnoses and (2) pharmacological or surgical procedures in the past 12 months. One additional child with CP completed the study protocol but was excluded when analysis revealed deterioration of performance with practice, suggesting that the participant was an outlier from the group. The demographics of the CP group are given in Table SI (online supporting information). Power analysis determined that a sample size of 39 would have 80% power to detect a moderate effect size of 0.70 with a significance level of p<0.05. Study procedures were approved by the institutional review boards at the University of New Mexico and the University of Southern California. Informed consent was obtained from a parent or guardian and participants over 14 years of age, and informed assent from participants under 14 years of age.

**Computer instrumentation and task**

The motor task used in this study was designed to enable participants to learn a discrete, coordinated upper limb movement using a lightweight lever. This adjustable lever was affixed to a frictionless vertical axle such that the lever movement was restricted to the horizontal plane above the surface of a table. A linear potentiometer attached to the base of the vertical axle recorded lever position information.

The target movement to be performed remained consistent throughout the task and consisted of two elbow extension–flexion reversal movements at specific amplitudes in a horizontal plane. The total duration of the target movement was 1000 ms. A target trajectory (position–time trace) was displayed on the computer monitor at the beginning of each trial for 2000 ms, after which the trajectory disappeared from the screen. After 1000 ms following target presentation, a ‘go’ signal was displayed, signalling the child to move the lever in order to replicate the target trajectory. Following the movement, after a delay of 2000 ms, either post-response (augmented) feedback was displayed on the computer screen or the screen remained blank for 5000 ms. Feedback consisted of (1) an overall numeric error score, the root mean square error (RMSE), for knowledge of results feedback and (2) a graphic representation of the participant’s response superimposed on the target movement pattern to give knowledge of performance feedback. The task goal was to replicate the target movement to minimize the RMSE.

**Experimental design**

The experiment was conducted on two consecutive days. On day 1, the acquisition phase, all participants practised the motor task for 200 trials, which consisted of four sessions of five 10-trial blocks separated by 3- to 4-minute breaks. On day 2, the retention phase, the participants were tested under two conditions: (1) a 10-trial no-feedback retention test block to determine the participants’ recall of the previous day’s practice reflecting the strength
of the motor skill memory representation previously developed; and (2) a 20-trial with-feedback reacquisition test block used as an additional test of motor memory indicating whether or not the learner returned to the previous day’s baseline. Both retention and reacquisition tests have been used previously to assess motor learning.9,12

Children were assigned to four experimental groups resulting in a 2 × 2 between-group design (groups: CP, typical development; feedback: 100%, 62%). In the reduced feedback subgroup, the relative frequency of feedback was progressively faded across the four sessions in the following manner: relative feedback frequency was 100% for session 1; 75% feedback frequency in session 2; 50% feedback frequency in session 3; and 25% feedback frequency in session 4. Out of a total of 200 trials in the acquisition phase, participants in the reduced feedback subgroup received feedback on 126 trials, thereby accounting for an overall 62% relative frequency of feedback.

Procedure
Before the acquisition phase, all participants were assessed for deficits in visual perception using the Motor-Free Visual Perception Test-316 and gross manual dexterity using the Box and Block Test.17 Both tests are reliable, valid measures with normative data for children. Prior to data collection, interrater reliability at or above 90% agreement was obtained between researchers during the testing of four children with typical development and three children with CP who were not included in the study. Additional measures of visual–motor perception and tactile sensibility of a subgroup of children with CP are reported elsewhere.18

Participants sat in front of a computer monitor with their testing forearm resting on a lightweight horizontal lever arm in the front plane of the body, grasping the handle of the lever as shown in Figure 1. Participants were asked to use their dominant hand (less involved hand for children with CP) to perform a coordinated arm movement. A sample trajectory was used to orient the participant to the task, allowing the experimenter to carefully explain the goal movement and feedback templates. This ensured that the child understood how to interpret the computer-displayed feedback to make his or her movements as accurate as possible (i.e. a lower RMSE and more accurate replication of the target trajectory). Once the experimenter determined that the child was adequately oriented to the task, the acquisition phase began, with participants practising the arm movement for four sessions consisting of five 10-trial blocks. One day later, the participants returned for the retention and reacquisition phases.

Data analysis
Performance accuracy and consistency were assessed separately for the acquisition, retention, and reacquisition phases. The dependent measure for accuracy was the RMSE, which is the average difference between the goal movement trajectory and the participant’s response, calculated over the participant’s total movement time.8 The RMSE was calculated for each trial and averaged into 10-trial blocks for analysis. Variable error was used as a

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**Figure 1:** Experimental set-up. The child moves the lever arm with his or her preferred hand to learn the spatiotemporal rapid arm movement task. Feedback of the child’s performance is presented on the second screen for all trials (100% feedback) or for a reduced number of trials (62% feedback). RMSE, root mean square error.
measure of consistency, calculated as the within-group variability about the mean RMSE for each block.

After confirming that RMSE and variable error were normally distributed using the Shapiro–Wilk test \(p>0.05\), separate \(t\) tests were conducted to assess group differences for age, Motor-Free Visual Perception Test-3 scores and Box and Block test scores. For the acquisition phase on day 1, a \(2 \times 2 \times 20\) analysis of variance (ANOVA) with repeated measures on the last factor was used (groups: CP, typical development; feedback: 100%, 62%; blocks: 1–20). Group and feedback were the between factors. For the day 2 retention session, a \(2 \times 2\) ANOVA was used for the no-feedback retention trials (groups: CP, typical development; feedback: 100%, 62%). Reacquisition performance was assessed using a \(2 \times 2 \times 2\) ANOVA with repeated measures on the last factor (groups: CP, typical development; feedback: 100%, 62%; blocks: 1–2). Post-hoc \(t\)-tests were conducted and Bonferroni correction was used to adjust \(p\) values for post-hoc analyses. All statistical tests were carried out using srs-13 software (IBM SPSS Statistics, IBM Corp., NY, USA) and the significance was set at \(p<0.05\).

**RESULTS**

**Demographic information**
The mean comparisons for the CP and typical development groups, as well as for feedback subgroups calculated through separate \(t\) tests for age, Motor-Free Visual Perception Test-3 scores and Box and Block test scores, are summarized in Table I. All children in both groups scored within age expectations on the Motor-Free Visual Perception Test-3. There was a significant difference between the typical development and CP groups; children with CP scored significantly higher than children with typical development \((p=0.01)\). However, no significant differences were found between the subgroups. Furthermore, there was no significant difference between the CP and typical development groups on the performance of the Box and Block test \((p=0.54)\).

**Acquisition phase**
The means of the performance error (RMSE) and consistency (with variable error) of the participants in all four experimental groups (children with CP and children with typical development who received 100% feedback; children with CP and children with typical development who received 62% feedback) during the acquisition, retention, and reacquisition phases are shown in Table II. Acquisition data are presented by session (1–4). Both children with CP and children with typical development benefited from practice, as indicated by increased performance accuracy across trials during the acquisition phase. Participants in all groups significantly improved their performance over the course of acquisition (practice effect: mean RMSE block 1, 41.01 [SD 12.89]; mean RMSE block 20, 15.91 [SD 5.79]; paired \(t\) test; \(t=11.348\); \(p<0.001\)).

Repeate-measures ANOVA for performance error (RMSE) resulted in no group–feedback interaction or main effect of feedback. As shown in Table II and Figure 2a, throughout the acquisition phase (sessions: 1–4) children with CP performed with greater error than the children with typical development, resulting in a group main effect \((F=1.217; p<0.001)\). Performance accuracy did not differ between the feedback subgroups of children with typical development in sessions 1 and 2; however, when feedback frequency dropped to 50% and 25% relative frequency in sessions 3 and 4 respectively, children who received 100% feedback performed with significantly less error than the children who received 62% feedback (session 3: \(p=0.006\); session 4: \(p=0.015\); Table II, Fig. 2b). Among children with typical development in the reduced feedback subgroup, performance accuracy during acquisition was decreased when feedback was reduced beyond a critical point. No significant difference in performance accuracy was found during the acquisition phase among children with CP, regardless of whether or not feedback was reduced \((p=0.092;\text{ Table II})\). However, those who received 100% feedback showed less error in each session than children with CP who received reduced feedback (see Table II, Fig. 2c).

Performance consistency (variable error) of group mean for the CP and typical development groups during the acquisition phase (sessions: 1–4) are shown in Figure S1 (online supporting information). The results of a repeated-measures ANOVA for variable error during acquisition resulted in no group–feedback interaction and no feedback

**Table I: Group mean (SD) scores for age, visual perception, and manual dexterity by feedback subgroup\(^a\)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Children with typical development ((n=20))</th>
<th>Children with spastic hemiplegic CP ((n=19))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100% feedback ((n=10))</td>
<td>62% feedback ((n=10))</td>
</tr>
<tr>
<td></td>
<td>100% feedback ((n=9))</td>
<td>62% feedback ((n=10))</td>
</tr>
<tr>
<td>Age (y:mo)</td>
<td>10.5 (1:8)</td>
<td>11.0 (2:0)</td>
</tr>
<tr>
<td></td>
<td>10.7 (1:7)</td>
<td>12.4 (2:7)</td>
</tr>
<tr>
<td></td>
<td>103.2 (12.4)</td>
<td>98.8 (13.2)</td>
</tr>
<tr>
<td></td>
<td>58 (6.0)</td>
<td>62 (7.0)</td>
</tr>
<tr>
<td></td>
<td>52 (6.0)</td>
<td>46 (10.0)</td>
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<tr>
<td></td>
<td>58 (6.0)</td>
<td>62 (7.0)</td>
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\(^a\)Separate \(t\) tests: \(p^1=p\) value for children with typical development, within-group difference (100% feedback and 62% feedback); \(p^2=p\) value for children with cerebral palsy (CP), within-group difference (100% feedback and 62% feedback); \(p^3=p\) value for between-group difference (children with typical development and children with CP).
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or group main effects. Overall, the performance consistency of children with CP was similar to that of the children with typical development (Table II; \( F=0.099; p=0.874 \)) and performance consistency was similar for feedback subgroups with the exception of session 3 for children with typical development (see Table II and Fig. S1a, variable error acquisition).

**Retention phase: no-feedback retention test**

The no-feedback retention test was administered as a measure of the children's learning during acquisition on the previous day. There was a significant main group effect present, with children with typical development demonstrating significantly less error than children with CP \((p=0.031)\). A significant main feedback effect was also present, with children receiving 100% feedback performing with significantly less error than those receiving reduced feedback during acquisition \((p=0.02)\). Retrospective power analysis using the delayed retention data indicated a high statistical power (effect size=0.70) to detect between-group learning differences. Although there was no significant group-feedback interaction \((p=0.96)\), which suggested that the effect of reduced feedback frequency was similar for children with CP and those with typical development (Fig. 2a), post-hoc analysis suggested the presence of feedback differences by group. Children with typical development who received 100% feedback during acquisition demonstrated significantly less error than the children who received reduced feedback \((p=0.017; \text{Fig. 2b})\). Similarly, children with typical development receiving 100% feedback showed less variability \((p=0.03; \text{Table II, variable error retention})\) than those receiving 62% feedback; however, the difference did not reach the level of significance with Bonferroni correction for multiple analyses. Differences between children with CP in the 100% and reduced feedback subgroups did not reach significance for RMSE \((p=0.186; \text{Fig. 2c})\) or variable error \((p=0.33; \text{Fig. S1c})\). Retrospective power analyses yielded a small effect size \((0.33)\). The lack of significance between the two feedback subgroups of children with CP appeared to be influenced by the large variability in the performance of children with CP (Table II, variable error retention).

Additional post-hoc analysis with Bonferroni correction revealed no other statistically significant subgroup differences. However, when comparing children’s performance (typical development vs CP) in the 100% feedback and reduced feedback subgroups, children with typical development demonstrated less error than children with CP during the 100% feedback \((p=0.05)\) and the reduced feedback condition \((p=0.20; \text{Fig. 2a})\).

There was no significant group-feedback interaction \((p=0.597)\) or main group effect \((p=0.718)\) for variable error during the no-feedback retention test, indicating no
differential effect of relative feedback frequency on variable error for children with CP and those with typical development. A significant main feedback effect ($p=0.038$) was present on retention. Post-hoc analysis revealed that the children with typical development who received 100% feedback demonstrated greater consistency in their performance during the retention phase than children with typical development receiving reduced feedback ($p=0.03$). The performance consistency of children with CP was similar whether they received 100% or reduced feedback.

**Re-acquisition phase: with-feedback retention test**

During the reacquisition phase, when feedback was reintroduced, the accuracy of performance of all participants improved. Feedback subgroup means indicate that children were able to match their best performance from the previous day during the practice acquisition phase. There was a significant main group effect present, with children with typical development demonstrating significantly less error than children with CP ($p=0.001$). Post-hoc analysis revealed that children with typical development completed the motor task with significantly less error than children with CP in both the 100% feedback subgroup ($p=0.02$) and the reduced feedback subgroup ($p=0.01$). During this reacquisition phase, all children benefited from additional feedback. In contrast to the no-feedback retention test, all children with typical development decreased their error with no significant performance differences between the 100% feedback and reduced feedback subgroups ($p=0.32$). Children with CP also demonstrated no significant differences between feedback subgroups when feedback was reintroduced ($p=0.09$). During the reacquisition phase, the performance consistency of children with typical development and children with CP groups was similar. There was no significant effect of feedback condition ($p=0.195$) or group ($p=0.189$) or interaction effects of feedback and group ($p=0.812$) on variable error.

**DISCUSSION**

Our results suggest that all children (typically developing and with CP) can benefit from practice with augmented feedback when learning a rapid goal-directed motor task. Both groups of children showed marked improvements in accuracy and consistency during the 200 acquisition trials with their performance preserved the following day during retention tests. Our findings documenting motor learning changes with augmented feedback are consistent with other studies of children with typical development and children with CP. Although other studies have reported positive effects of feedback manipulations (mirror visual feedback, knowledge of performance, etc.) on skill acquisition in children with CP, the results did not include retention, transfer, or reacquisition tests to make any inferences about motor learning.

Our study compared the performance of children with typical development and children with hemiplegic CP in learning the same motor task in two feedback conditions. Children with CP used their preferred (less involved) hand, which reportedly requires less visual monitoring during manual tasks.
As hypothesized, in both feedback conditions, children with CP demonstrated more error than children with typical development in terms of accuracy and consistency during the acquisition, retention, and reacquisition phases, suggesting motor execution difficulties. Our results were similar to those reported in adults with unilateral brain damage,\(^9\) who demonstrated more error than age-matched control adults learning a motor task. Similarly, Harbourne\(^5\) reported that children with CP, compared with children with typical development, displayed more error in terms of speed and error detection while learning to slide a lever along a track with their preferred or less involved arm. Interestingly, Harbourne\(^5\) also reported that half of the children with CP scored within the range of their typically developing peers, while the rest scored lower than the typically developing comparison group. Gagliardi et al.,\(^26\) using a sequence learning task, also found that children with CP performed at a comparable level to children with typical development, but required more trials to be successful. These studies suggest motor execution differences in children with brain lesions; however, cognitive learning of the skill appears to be dependent upon individual abilities and cognitive effort, as proposed in the Challenge Point Framework.\(^15\)

Consistent with our second hypothesis, children with hemiplegic CP used feedback in a similar manner to children with typical development. When comparing performance between all children who received 100% and those receiving 62% feedback during skill acquisition trials, the reduced feedback condition resulted in more error during acquisition, retention, and reacquisition. However, responses to different frequencies of feedback during the retention test were clearer in the typical development groups than in the CP feedback subgroups. Children with CP who practised with 100% feedback consistently demonstrated less error than peers in the reduced feedback group in the acquisition phase, retention test, and reacquisition test; however, these differences in performance did not reach levels of significance. Overall results of our study suggest that children receiving 100% feedback demonstrated greater learning. In contrast, Hemayattalab and Rostami\(^29\) compared retention of throwing skills in children with hemiplegic CP who practised in 100%, 50%, and no feedback conditions. Those who practised with 50% feedback performed with the least error, suggesting that increased feedback may interfere with their motor learning. The discrepancy between our findings and these researchers may be the complexity of the task learned since children in our study practised a rapid spatially and temporally constrained task. In another study,\(^18\) children with typical development practised two simple and complex throwing tasks. During the simple throwing task, children benefited the most from 33% feedback; however, children who received 100% feedback as they learned the complex throwing task performed with less error in a delayed retention test and with greater accuracy in a transfer test to a new motor task. Other researchers reported greater learning when frequent feedback is provided.\(^27,28\) Capio et al.\(^27\) documented reduced errors during the early stages of practice when children receive frequent feedback, a condition with less cognitive processing load. Wulf et al.\(^28\) reported beneficial effects when children learning a soccer throwing task received 100% feedback during practice and concluded that frequent external-focus feedback served as a potent reminder to maintain attention and motivation. Our findings are consistent with these studies, supporting the use of 100% feedback during complex motor skill acquisition.

Recent evidence suggests that children with right hemiplegic CP (left hemisphere lesions) have compromised capacity for motor planning in addition to motor execution differences.\(^29\) In our study, sample size in the different feedback subgroups was low, therefore we were unable to compare children with right and left hemiplegia to determine hemispheric differences. We also were unable to compare the performance of younger and older children with CP using statistical procedures.

Limitations of this study include the small sample size and the learning task used. By controlling for additional variables influencing learning (visual–perceptual, motor, academic performance, etc.), our inclusion criteria limited the number of participants and the ability to generalize results to all children with hemiplegic CP. Larger studies may permit comparisons of children with CP that consider brain lesion location, functional level, and age group to increase our understanding of how children with CP best utilize feedback as they learn motor skills. Our motor learning task was selected because it was a previously researched paradigm which allowed comparisons between adults and children with and without hemiplegia. Thus, generalization of results to children with CP learning daily routines and tasks is limited.

In summary, our results suggest children with hemiplegic CP use feedback in a similar manner to children with typical development when learning new skills with their less involved hand, but demonstrate less accuracy and consistency. All children demonstrated greater retention of the motor skill learned if frequent feedback was provided; however, in children with CP, more trials with augmented feedback may be required. Ultimately, the use of feedback to augment intervention should be individually designed using the most up-to-date motor learning principles with periodic monitoring of intervention effects.

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authors have stated that they had no interests that might be perceived as posing a conflict or bias.

**SUPPORTING INFORMATION**
The following additional material may be found online:

**REFERENCES**


**Table S1:** Cerebral palsy participant demographics.

**Figure S1:** Block means for variable error by participant group.