Motor Learning in Children: Feedback Effects on Skill Acquisition

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Background and Purpose. Reduced feedback during motor skill practice benefits motor learning. However, it is unknown whether these findings can be applied to motor learning in children, given that children have different information-processing capabilities than adults. The purpose of this study was to determine the effect of different relative frequencies of feedback on skill acquisition in children compared with young adults.

Subjects. The participants were 20 young adults and 20 children.

Methods. All participants practiced 200 trials of a discrete arm movement with specific spatiotemporal parameters. Participants from each group (adults and children) were randomly assigned to either a 100% feedback group or a reduced (62% faded) feedback group. Learning was inferred from the performance on the delayed (24-hour) retention and reacquisition tests.

Results. All participants improved accuracy and consistency across practice trials. During practice, the adults performed with significantly less error than the children. Adults who practiced with reduced feedback performed with increased consistency during the retention test compared with those who practiced with 100% feedback. In contrast, children who received reduced feedback during practice performed with less accuracy and consistency during the retention test than those who received 100% feedback. However, when feedback was reintroduced during the reacquisition test, the children in the reduced feedback group were able to improve their performance comparable to those in the 100% feedback group.

Discussion and Conclusions. During motor learning, children use feedback in a manner different from that of adults. To optimize motor learning, children may require longer periods of practice, with feedback reduced more gradually, compared with young adults.

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On a daily basis, children engage in motor activity that leads to the progressive development of motor skills. Some of this activity leads to skill in functional tasks such as running, jumping, kicking, and throwing. Other motor activity leads to the acquisition of fine motor skills that involve eye-hand coordination, such as playing a video game or using a computer. Despite the extensive literature on the effects of feedback during motor task practice on motor skill acquisition and learning in adults,[1–7] there is a paucity of literature in the area of motor learning in children.

Adults who practice motor skills in reduced feedback conditions perform with greater accuracy and consistency in a delayed retention test compared with those who practice with feedback provided during every practice trial.[1,3–6] Reduced feedback practice conditions are hypothesized to increase information-processing demands during practice that are advantageous to the relatively permanent effects associated with motor learning observed in a delayed retention test.[8–10] In contrast, frequent feedback may guide the learner to a correct response during practice and interfere with the problem-solving processes associated with more effortful practice.[8,9]

Cognitive effort during practice, while advantageous for some people, may exceed the optimal capability for other individuals, especially those with reduced or impaired information-processing abilities. Guadagnoli and Lee[11] have proposed the Challenge Point Framework, which suggests that motor learning depends on the level of challenge emerging from an interaction of the information-processing capability of the learner, task demands, and practice condition. This framework serves as a model to predict the interaction that may occur when the challenge posed by a practice condition exceeds the information-processing capability of the learner. According to this framework, challenge is required to engage the cognitive processes associated with motor learning. There is a point of optimal challenge that yields maximum practice benefits when optimal cognitive effort is invoked. A level of challenge below or above this optimal challenge point may attenuate learning. That is, conditions that demand too much cognitive effort may interfere with learning effects.[11]

It is well established that children have different information-processing capabilities compared with adults.[12,13] Children have differences in cognitive processes such as selective attention[14] and speed of information processing[15,16] that increase with age. In addition, children use different strategies to process information compared with adults in tasks that require visuospatial working memory,[17,18] object recognition memory,[19] verbal learning,[20] copying spatial patterns,[21] or higher-level attention focusing.[22,23] These differences in cognitive ability may contribute to motor learning differences between children and adults,[12] bringing into question the generalizability of motor learning principles derived primarily from young adults to children. Specifically, it is unknown whether reduced frequency of feedback during practice benefits motor learning in children in a manner that is similar to or different from that of adults.

The present study was designed to investigate the effect of different frequencies of feedback during practice on acquisition and retention of a fast, discrete motor skill in children compared with young adults. Based on the Challenge Point Framework,[11] we hypothesized that children who practiced in a reduced feedback frequency condition would not realize the same motor learning benefits compared with young adults. Our long-term goal is to understand the effects of feedback schedules on motor learning in children in order to provide additional insights regarding optimizing feedback delivery during skill acquisition in children with and without neurological impairments.

Method

Participants

Twenty young adults (12 male, 8 female; mean age=25.6 years, SD=2.5, range=22–30) and 20 children who were healthy and developing typically (12 male, 8 female; mean age=10.7 years, SD=2.0, range=8–14) voluntarily participated in the study. All participants were recruited from the greater Los Angeles area. Prior to participating in the experiment, informed consent was provided by the adult participants, and parental consent and child assent were obtained for the children who participated. Inclusion criteria were young adults aged 21 to 35 years and children aged 8 to 14 years who were developing typically and performing at grade level in school. Exclusion criteria were any orthopedic or neurological problems that would interfere with the ability to perform a coordinated arm movement. All participants used their dominant arm to practice the movement task. All participants were evaluated for visual perception and gross motor dexterity.

Instrumentation and Task

The motor task was to learn a discrete, coordinated arm movement using a lightweight lever. This 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. The handle at the end of the lever was adjusted to accommodate the participant's forearm. A linear potentiometer attached to the base of the vertical axle recorded lever-position information. Signals from the potentiometer were converted to digital signals by an A/D board of a computer and sampled at 1,000 Hz to provide feedback on the computer monitor. The template software program (Allen Weekly, 2004) was used for manipulation of the movement trajectory and the interval duration and for data storage for off-line analysis of each trial.

The coordinated arm movement consisted of 2 elbow extension-flexion reversal movements, each of specific amplitude, performed in the horizontal plane. The total duration of the target movement was 1,000 milliseconds. A target trajectory (position-time trace) was displayed on the computer monitor at the beginning of each trial for 2,000 milliseconds, after which the trajectory disappeared from the screen. After 1,000 milliseconds following target presentation, a “go” signal was displayed, at which point the subject was instructed to move the lever in order to replicate the target trajectory. After a delay of 2,000 milliseconds following the movement, post-response (augmented) feedback was displayed on the computer screen for 5,000 milliseconds during the feedback trials. For the no-feedback trials, the screen remained blank for the 5,000 milliseconds. This feedback consisted of: (1) an overall numeric error score (root mean square error [RMSE]) and (2) a graphic representation of the participant’s response superimposed on the target movement pattern. Figure 1 shows examples of individual trials and post-response feedback display.

Experimental Design

The experiment was conducted on 2 consecutive days. On day 1 (acquisition phase), all of the participants practiced the motor task for 200 trials. These trials were presented as four 50-trial sessions separated by 3- to 4-minute breaks. On day 2 (retention phase), the participants were tested under 2 conditions. A 10-trial, no-feedback retention test was used to determine the participants’ recall of the previous day’s practice. The no-feedback retention test is a recall test that reflects the strength of the motor skill memory representation developed during practice. This was followed by 20 additional trials with feedback to assess reacquisition performance. The reacquisition test is used as an additional test of motor memory and reflects the relative benefits of the previous day’s practice (ie, whether the learner returned to the previous day’s baseline or not) and the learner’s ability to respond when additional practice trials are provided. Both retention and reacquisition tests have been used previously to assess motor learning.[24]

Children and adults were randomly assigned to either a 100% feedback group or a reduced (62% faded) feedback group. In the 100% feedback condition, the participants received augmented feedback after every trial during the acquisition phase. In the reduced feedback group, the relative frequency of feedback was progressively faded across four 50-trial sessions in the following manner: for session 1, relative feedback frequency was 100%; in session 2, the feedback frequency was reduced to 75%; in session 3, the feedback frequency was reduced to 50%; and in session 4, the feedback frequency was further reduced to 25%. Out of 200 trials in the acquisition phase, participants in the reduced feedback group received feedback on 126 trials, thereby accounting for an overall 62% relative frequency of feedback. Thus, we had 4 experimental groups: (1) young adults who received 100% feedback, (2) children who received 100% feedback, (3) young adults who received reduced feedback, and (4) children who received reduced feedback.

Procedure

Prior to the acquisition phase, all participants were assessed for deficits in visual perception with the Motor-Free Visual Perception Test (MVPT-3). The MVPT-3 is a reliable and valid norm-referenced measure of overall visual perceptual processing ability in children and adults[25] that assesses various aspects of visual perception such as visual memory and spatial relations that may affect visuomotor learning. Gross manual dexterity was assessed using the Box and Block Test, a reliable and valid measure of hand gross motor skills.[26,27] Both tests were conducted by an examiner who was trained and tested for reliability.

During practice, participants sat comfortably in front of the computer monitor with their testing forearm along the arm of the lever and their hand grasping the lever handle. A sample trajectory was used to orient the participant to the task. Sample goal movement and feedback were explained carefully to the participants. The experimenter and the participants reviewed templates of a sample target trajectory and superimposed feedback trajectory to ensure that the participants understood how to interpret computer-displayed feedback. The participants were instructed that, during the experiment, they were to practice the goal movement and use feedback to make their movements as accurate as possible (ie, lower RMSE and replicate the target trajectory). Care was taken to ensure that the children understood how to interpret the augmented feedback. When the experimenter determined that the participants were adequately oriented to the task and the augmented feedback, the acquisition phase was begun. Participants practiced the arm movement for four 50-trial sessions. After session 1 (trials 1–50), all the participants rated the level of perceived difficulty of the task on a vi-

Table 1.
Means (Standard Deviation) for Age, Visual Perception, Motor Skills, and Reported Difficulty Scores for Young Adults and Children by Feedback (FB) Group (100%, 62%) and Between- and Within-Group Differences[a]

Variable	Young Adults (n=20)			Children (n=20)			
	100% FB	62% FB	P^1	100% FB	62% FB	P^2	P^3
Age, y	26.3 (2.9)	25.1 (2.1)	.29	10.4 (1.7)	11 (2.0)	.52	<.001
Motor-Free Visual Perception Test-3, %	94.7 (2.8)	96.4 (3.4)	.26	93.8 (5.0)	88.7 (8.9)	.13	.065
Box and Block Test, no. of blocks transferred per minute	72 (4)	72 (4)	.99	58 (6)	62 (7)	.30	<.001
Level of perceived difficulty, visual analog scale score (0–10)	5.05 (0.95)	5.35 (0.81)	.56	5.3 (0.91)	5.5 (0.97)	.71	.395

[a] Separate *t* tests: P^1=*P* value for young adult within-group difference (100% FB and 62% FB), P^2=*P* value for children within-group difference (100% FB and 62% FB), P^3=*P* value for between-group difference (young adults and children).

sual analog scale ranging from 0 (little difficulty) to 10 (too difficult to perform). 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.[28] The RMSE* was calculated for each trial and averaged into 10 trial blocks for analysis. Variable error was used as a measure of consistency, calculated as the within-subject variability about the mean RMSE for each 10-trial block.

Separate *t* tests were conducted to assess group differences for age, MVPT-3 scores, Box and Block Test scores, and reported scores for level of perceived difficulty. For the acquisition phase on day 1, a group (young adults, children) × feedback (100% feedback, reduced feedback) × block (blocks 1–20) analysis of variance (ANOVA) with repeated measures on the last factor was used. Group and feedback were the between factors. For the day 2 retention session, a group (young adults, children) × feedback (100% feedback, reduced feedback) ANOVA was used for the no-feedback retention trials. Reacquisition performance was assessed using a group (young adults, children) × feedback (100% feedback, reduced feedback) × 2 block (blocks 1–2) ANOVA with repeated measures on the last factor. Effect size was calculated as a measure of power and to determine the magnitude of between-group differences. The effect size was reported, according to established criteria,[29] as small (<0.41), moderate (0.41–0.70), or large (>0.70). In addition, a retrospective power analysis was included to verify significant group differences. For all statistical tests, the significance level was set at *P*<.05. We used SPSS, version 13.0,† statistical software for all statistical analyses.

* $RMSE=\Sigma (xi-T)^{1/2}/1{,}000$, where xi=participant position at time i and T=target position at time i.

† SPSS Inc, 233 S Wacker Dr, Chicago, IL 60606.

Results

Demographic Information

Group mean comparisons for age, MVPT-3 scores, Box and Block Test scores, and reported scores for level of perceived difficulty are summarized in Table 1. The adult and children groups differed significantly from each other in age (*P*<.001) and performance on the Box and Block Test (*P*<.001). Adults demonstrated greater gross motor dexterity compared with children, as indicated by significantly more blocks transferred in 1 minute during the Box and Block Test (young adults: mean number of blocks=72, SD=4; children: mean number of blocks=60, SD=7; *P*<.05). There was no significant difference between the children and adults on the performance of the MVPT-3 (*P*=.065), suggesting that both groups had normal, age-appropriate visual perception. Adults and children reported similar levels of perceived difficulty with the task (*P*=.395). Within each age group, there were no significant differences between the feedback groups for age, MVPT-3 scores, Box and Block Test scores, and reported scores for level of perceived difficulty (*P*>.05).

Performance Accuracy

Acquisition phase. Table 2 shows the means (SD) for performance error (RMSE) and consistency (variable error [VE]) of the participants in all 4 experimental groups (young

Table 2.
Performance Error (Root Mean Square Error [RMSE]) and Consistency (Variable Error [VE]) Block Means and Standard Deviations (in Parentheses) for the Acquisition Phase (Day 1) and Retention Phase (Day 2) for Young Adults and Children by Feedback (FB) Group (100%, 62%)[a]

Variable	Young Adults (n=20)			Children (n=20)			
	100% FB	62% FB	P^1	100% FB	62% FB	P^2	P^3
RMSE							
Acquisition	12.19 (3.4)	11.6 (3.7)	.60	15.55 (2.8)	18.33 (5.6)	.04	<.001
Session 1	17.24 (7.3)	17.30 (5.3)	.98	24.76 (8.1)	26.75 (8)	.39	<.001
Session 2	11.22 (2.2)	10.26 (2.3)	.36	14.58 (5)	15.68 (4.5)	.52	<.001
Session 3	10.47 (1.47)	9.48 (1.7)	.19	11.48 (2.7)	16.28 (5.3)	.006	<.001
Session 4	9.84 (1.3)	9.39 (1.2)	.45	11.39 (2.3)	14.62 (4.2)	.015	<.001
Retention (no-FB)	14.51 (4.5)	12.65 (3.9)	.34	13.23 (3.8)	19.48 (6.4)	.017	.075
Reacquisition							
Block 1	10.67 (3.2)	10.82 (3.5)	.81	12.5 (3)	13.71 (3.3)	.32	.003
Block 2	9.08 (2.1)	9.49 (2.5)		11.26 (2)	12.04 (3.6)		
VE							
Acquisition	4.9 (1.9)	4.6 (1.8)	.51	6.9 (2.8)	7.4 (2.7)	.45	<.001
Session 1	6.42 (2.7)	6.87 (2.7)	.53	9.9 (3.3)	9.21 (3.5)	.38	<.001
Session 2	4.83 (2)	4.46 (2)	.52	7.18 (3.1)	6.64 (2.5)	.61	.001
Session 3	4.36 (1.3)	3.55 (1.3)	.05	5.26 (2.3)	7.04 (2.5)	.02	<.001
Session 4	3.98 (1.4)	3.52 (1.3)	.29	5.48 (2.4)	6.8 (2.5)	.06	<.001
Retention (no-FB)	6.55 (2.3)	3.96 (1.5)	.009	5.05 (1.9)	7.4 (2.7)	.03	.17
Reacquisition							
Block 1	4.89 (1.5)	4.02 (1.6)	.70	4.9 (1.6)	6.3 (2.2)	.11	.019
Block 2	3.87 (1.2)	4.31 (1.8)		4.6 (0.6)	5.4 (3.2)		

[a] Group (young adult, children) × FB (100%, 62%) × block repeated-measures analysis of variance results: P^1=*P* value for young adult within-group difference (100% FB and 62% FB), P^2=*P* value for children within-group difference (100% FB and 62% FB), P^3=*P* value for between-group difference (young adults and children).

adults and children who received 100% feedback and young adults and children who received reduced feedback) during the acquisition, retention, and reacquisition phases. Both children and adults benefited from practice, as indicated by increased performance accuracy across trials during the acquisition phase (block main effect: for block 1, mean RMSE=35.8, SD=13.4; for block 20, mean RMSE=11.58, SD=3.44; *P*<.001). As shown in Table 2, throughout the acquisition phase the children performed with greater error than did the young adults, resulting in a group main effect (*P*<.001). Group differences in baseline performance accuracy were evident in block 1; however, by the end of practice, the children had improved such that there was no significant group × block interaction (*P*=.270). Figure 1 shows typical individual trial data for a young adult and a child during early and late practice, in which improvement in accuracy of performance was evident.

Performance accuracy during the acquisition phase was similar in adults, regardless of whether feedback was reduced or not (*P*=.60, Fig. 2B). In contrast, children who received reduced feedback demonstrated more error than children who received 100% feedback on every trial (*P*=.04, Fig. 2C). The locus of the performance differences between the 2 groups of children is evident between blocks 10 and 11 in Figure 2C. Performance accuracy did not differ between the 2 groups of children in session 1 (*P*=.39) or session 2 (*P*=.52). However, when feedback frequency dropped from 75% relative frequency in session 2 to 50% and 25% relative frequency in sessions 3 and 4, respectively, the children who received reduced feedback performed with significantly more error than the children who received 100% feedback (session 3: *P*=.006; session 4, *P* =.015). For the children in the reduced feedback group, performance accuracy during practice was decreased when feed-

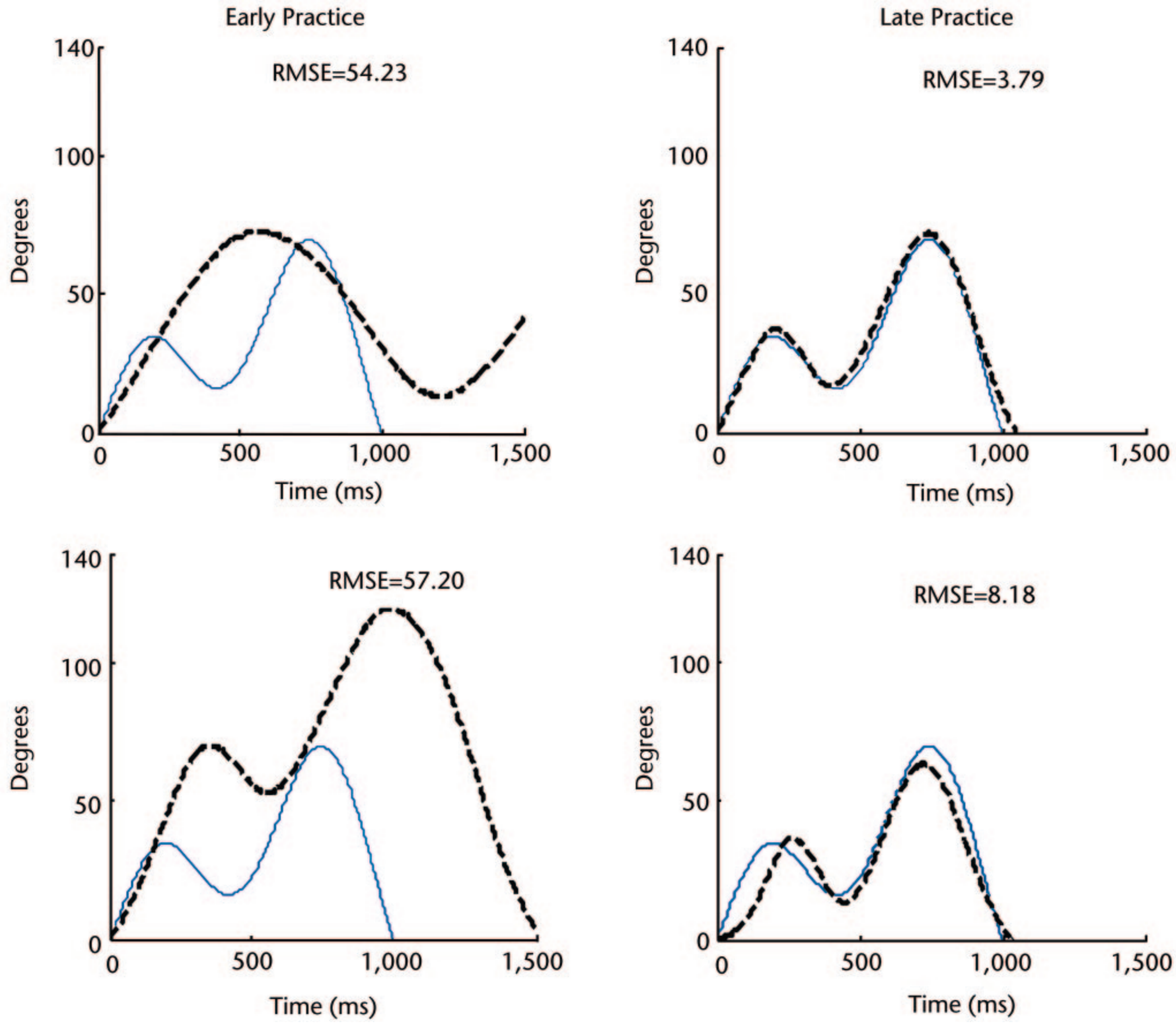

Figure 1.
Representative trial from early practice (left) and late practice (right) in a young adult (top row) and a child (bottom row). The blue line represents the target, and the dashed line represents the participant's trajectory. RMSE=root mean square error.

back was reduced beyond a critical point.

Retention phase: no-feedback retention test. During the no-feedback retention test, there was a significant group × feedback interaction (P=.011), which suggested that the effect of reduced feedback frequency was different for young adults and children (Fig. 2A). The 2 adult groups performed with similar accuracy on the no-feedback retention test (P=.337, Fig. 2B). The children who received reduced feedback, however, were significantly less accurate (higher RMSE) than the children who received 100% feedback (P=.017, Fig. 2C). Retrospective power analysis using the delayed retention data indicated a high statistical power (0.92) to detect between-group learning differences. *Post hoc* testing showed that the locus of interaction was the significant difference between the children and the adults who received reduced feedback (P=.01, Fig. 3). When children practiced the task under reduced feedback conditions, their retention performance was significantly less accurate than that of

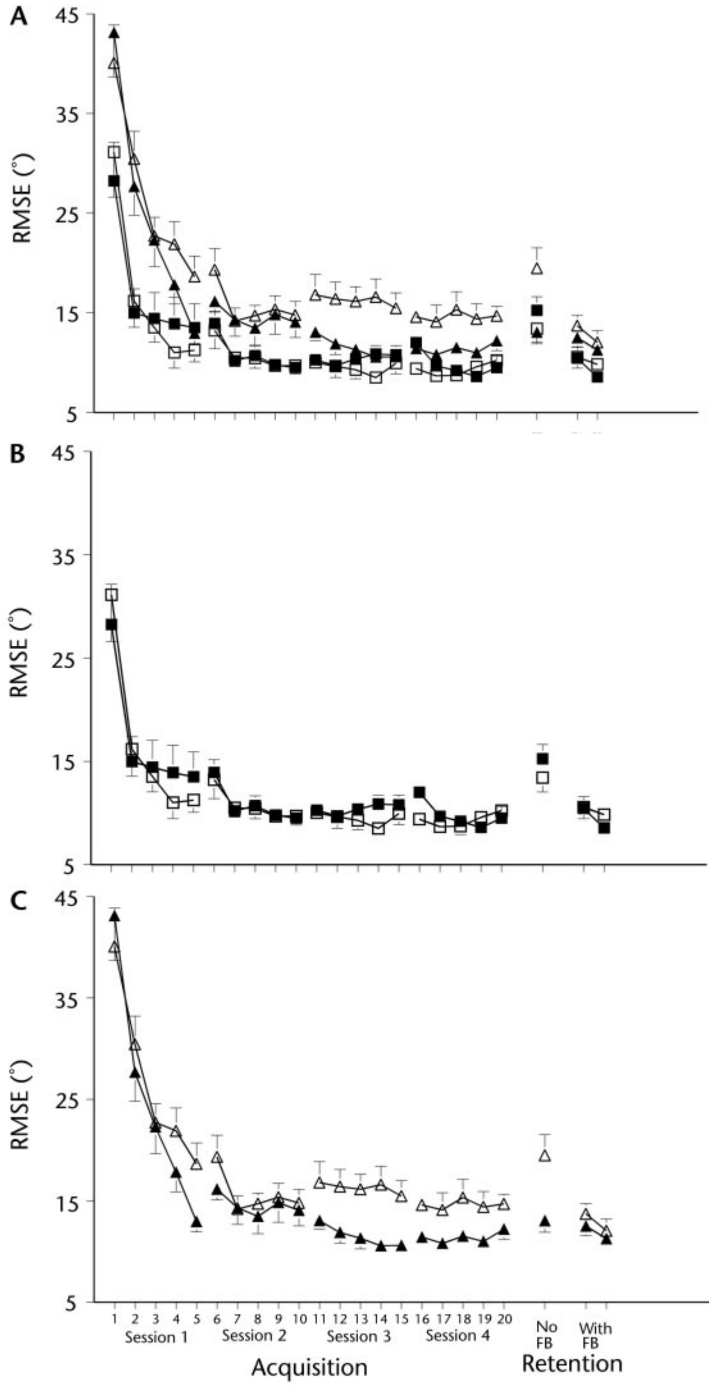

Figure 2.
Block means (±SE bars) for root mean square error (RMSE) during acquisition, retention (no feedback [FB]), and reacquisition (with FB) phases for young adults and children: (A) all groups: young adults who received 100% FB (closed squares), young adults who received 62% FB (open squares), children who received 100% FB (closed triangles), and children who received 62% FB (open triangles); (B) young adult groups only, and (C) children groups only.

adults who practiced in the same reduced feedback condition.

Reacquisition phase: with-feedback retention test. During the reacquisition phase, when feedback was reintroduced, the accuracy of performance of all participants improved across the 2 blocks (for block 1, mean RMSE=11.93, SD=3.39; for block 2, mean RMSE=10.47, SD=2.8; P=.013). Adults continued to perform with more accuracy than children (P=.003). There was no significant effect of feedback or group × feedback interaction. However, when feedback was reintroduced, the children who received reduced feedback performed as accurately as the children who received 100% feedback (P=.33), despite their less accurate performance on the no-feedback retention test.

Performance Consistency

Acquisition phase. Figure 4 shows the group means for VE for both acquisition and retention trial blocks for the young adults and children. Each group improved their performance consistency (reduced their VE) during the acquisition phase, which resulted in a block main effect for VE (for block 1, mean VE=11.7, SD=5.5; for block 20, mean VE=5.1, SD=2.6; P<.001). Throughout the acquisition phase, the children had significantly less performance consistency (higher VE) than the young adults, which yielded a significant group main effect (Tab. 2, P<.001). Performance consistency during the acquisition phase was not affected by feedback (P=.83). In addition, there was no significant group × feedback condition interaction for the acquisition phase (P=.31). Furthermore, during the acquisition phase, the children who received 100% feedback demonstrated significantly more performance consistency than the children who received reduced feedback (P=.04).

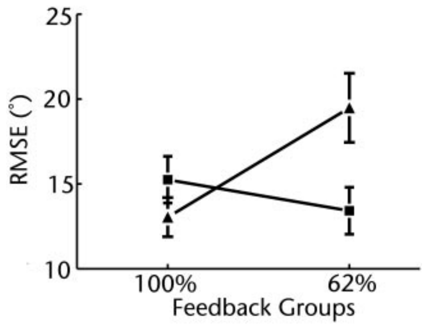

Figure 3.
Block means (±SE bars) for root mean square error (RMSE) during retention (no feedback) phase for interaction effects between young adults (solid squares) and children (solid triangles).

Retention phase: no-feedback retention test. There was a significant group × feedback interaction (P=.001) for VE during the no-feedback retention test, indicating a differential effect of relative feedback frequency on VE for the children and young adults (Fig. 5). *Post hoc* analysis revealed that the young adults who received reduced feedback had more consistent performance during the retention phase than the young adults who received 100% feedback (P=.009). In contrast, children who practiced with 100% feedback were more consistent in retention than children who practiced with reduced feedback (P=.03). Further analysis indicated that children who practiced with reduced feedback were not as consistent as adults who practiced with reduced feedback (P=.003). Although the difference in VE between the young adults and the children who received 100% feedback did not reach significance (P=.136), a moderate effect size (0.69) indicates that a larger sample may be required to show significant differences.

Reacquisition phase: with-feedback retention test. During the reacquisition phase, adults were more consistent in their performance than children (P=.019). There was no significant effect of feedback condition (P=.315) or interaction effects of feedback and group (P=.138) on VE.

Discussion and Conclusions

Motor Skill Performance and Learning Differences Between Children and Adults

When provided with the same number of practice trials as adults, children who received 100% feedback during the acquisition phase were more accurate and consistent on a delayed retention test than children who received a reduced feedback schedule. On the other hand, and consistent with previous literature, young adults who practiced with reduced feedback were more consistent during the delayed retention test compared with those who received 100% feedback. There was no difference in learning accuracy between the 2 adult groups.

During the acquisition phase, we found that the children's performance was less accurate than that of the adults. Bo et al[30] demonstrated that children have higher error and variability in their performance compared with adults on tasks that require visuomotor transformations. We also observed that the adults had better gross motor dexterity than the children, as reflected in higher scores on the Box and Block Test, a test that required eye-hand coordination. In addition, because of their limited experience with movement skills, children have less ability to pre-program ballistic aiming movements and, therefore, rely on online adjustments.[31,32] However, with practice, children develop the ability to program the ballistic phase of movements comparable to that of adults.[31] This was evident in our findings, which showed that the children who received feedback after every trial performed comparably to the adults during the end of the acquisition and retention trials. Our study extends the findings regarding performance differences between children and adults in that it is the first motor learning study to: (1) examine differences in the process of skill acquisition during practice between 8- to 14-year-old children who are developing typically and young adults, (2) investigate the influence of feedback frequency on children compared with adults, and (3) incorporate a retention test in order to understand the influence of feedback frequency during practice on motor learning in children.

We demonstrated that practice was less effective for the children in the reduced feedback practice condition. This finding was substantiated by less accurate and less consistent performance of the children who received reduced feedback compared with the children who received 100% feedback during sessions 3 and 4, when feedback was reduced to relative frequencies of 50% (during trials 101–150) and 25% (during trials 151–200), respectively. Furthermore, the less effective practice for the children who received reduced feedback is evident in their less accurate performance during the delayed no-feedback retention test compared with the young adult groups or the children who received feedback on every trial. Despite the challenging practice on day 1, the children who received reduced feedback did benefit from practice, as reflected in accuracy and consistency comparable to that of the children who received 100% feedback when additional practice (20 trials) with feedback was provided on day 2 during the reacquisition phase.

Our results are consistent with the predictions of the Challenge Point Framework,[11] which suggests that task demands, learner characteristics, and practice conditions interact to influence the level of challenge posed to the learner during practice. There is a point of optimal challenge at which the practice benefits for learning are maximized because the practice invokes a learner-appropriate level of cognitive effort. If the level of challenge exceeds this optimal challenge point, the resulting cognitive effort may be well beyond the information-processing capability of the learner, thereby interfering with learning benefits. The Challenge Point Framework further predicts that this optimal challenge point will differ for learners with different information-processing capabilities and skill levels such as children and adults. Therefore, practice conditions that may foster learning in adults may not be as beneficial for children.

Reduced Feedback and Information-Processing Demands

Practice with reduced feedback frequency benefits motor skill acquisition in young adults who are healthy by promoting critical cognitive processing that enhances retention. When augmented error feedback is withdrawn, the learner is forced to interpret and process intrinsic feedback provided by proprioception and vision of their own movement for detecting errors; this enhances the memory representation of the skill and results in better motor learning.[33] This processing requires cognitive effort, which is the mental work involved in attending to and interpreting intrinsic feedback and planning the next movement.[10,34] This enhanced cognitive effort during practice is thought to be critical in promoting motor skill learning.[10,34] Conversely, the learning benefits of practice with reduced feedback frequency depend on the ability of the learner to process the additional cognitive demands. For a practice condition to benefit motor learning, it should invoke an optimal cognitive effort.[11] If the cognitive demands of the practice condition exceed the cognitive capability of the learner to pro-

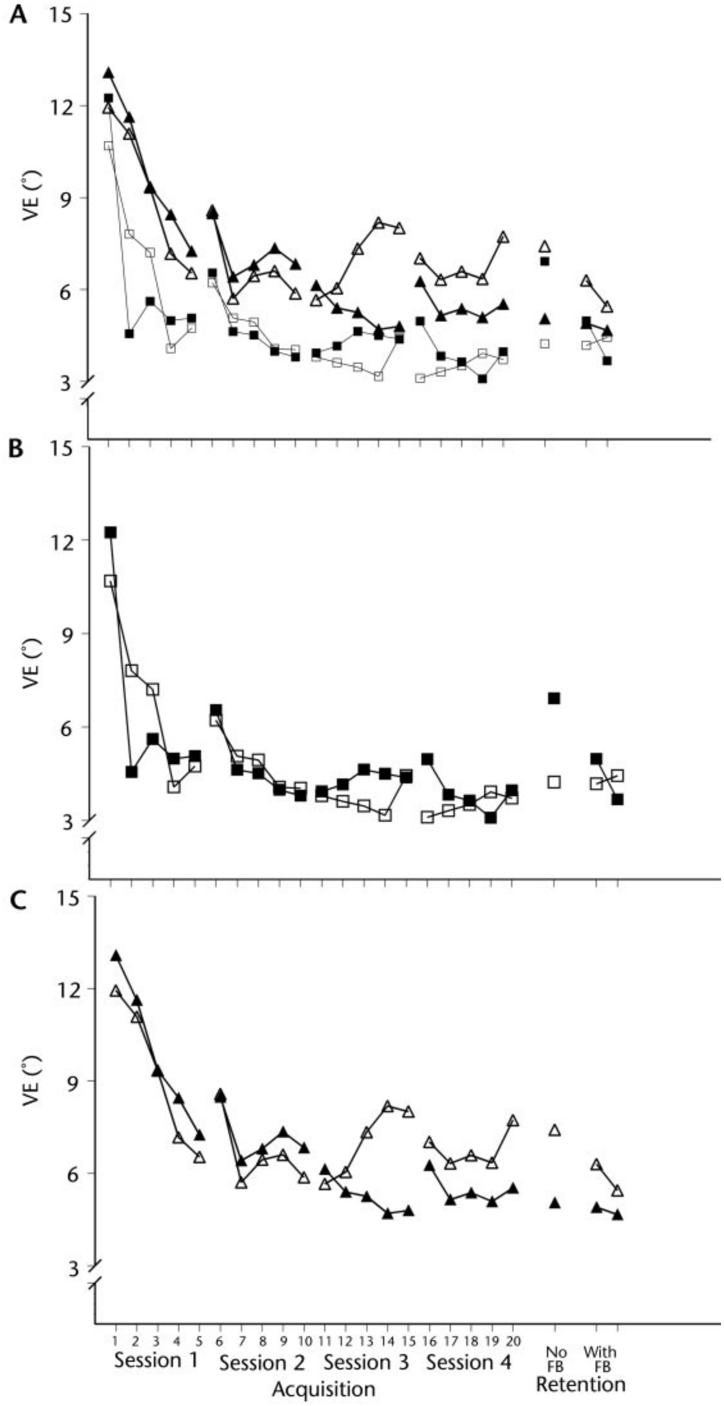

Figure 4.
Block means (±SE bars) for variable error (VE) during acquisition, retention (no feedback [FB]), and reacquisition (with FB) phases for young adults and children: (A) all groups: young adults who received 100% FB (closed squares), young adults who received 62% FB (open squares), children who received 100% FB (closed triangles), and children who received 62% FB (open triangles); (B) young adult groups only, and (C) children groups only.

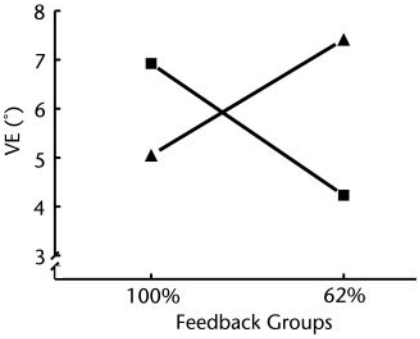

Figure 5.
Block means (±SE bars) for variable error (VE) during retention (no feedback) phase for interaction effects between young adults (solid squares) and children (solid triangles).

cess information, the learning benefits may be attenuated.[11,35]

Differences in cognitive processing capabilities of children compared with adults have been demonstrated on a Fitt's task, where children's accuracy was significantly less than that of adults as the task difficulty increased.[36] In the Fitt's task, the participant moves alternately between 2 targets with instruction to move as fast and accurately as possible. Task difficulty is increased by either increasing the distance between the 2 targets or decreasing the target width. With increased task difficulty, participants need to process more information about the target distance and width, which is reflected in decreased accuracy when the movement speed is experimentally controlled. Children consistently demonstrate less accuracy than adults on a Fitt's task. Children have less efficient ability to attend to and interpret intrinsic feedback from various sensory systems and more difficulty in detection and estimation of movement error.

Children use different strategies compared with adults to process proprioceptive information for planning and execution of reaching movements.[37] There is an improvement in capability to integrate visual and proprioceptive afferent inputs with age, resulting in a more efficient motor performance in older children.[38] Furthermore, there is evidence to suggest that children rely more on extrinsic feedback compared with adults.[38] These differences in information processing between children and adults may underlie the differences in the use of feedback for motor skill acquisition.

Our interpretation is that the reduced feedback schedule used in this study exceeded the optimal challenge point in children and invoked a degree of cognitive effort that taxed their information-processing capability. This detrimental effect of reduced feedback frequency in children was evident during the acquisition phase (sessions 3 and 4). The performance of the children who received reduced feedback deteriorated in sessions 3 and 4, when the feedback frequency was reduced to 50% and 25%, respectively. This detrimental effect also was carried over to the no-feedback retention test in the children who received reduced feedback. These findings suggest that reducing the feedback frequency beyond a critical point (optimal challenge point) during the acquisition phase was detrimental to motor performance and learning in these children.

Although other investigators have reported the differential effects of feedback manipulations (precision and knowledge of results [KR] delay) on motor performance in children and adults,[39–42] none of these studies used a retention, transfer, or reacquisition test in order to make any inferences about motor learning.[43] We used retention and reacquisition tests to demonstrate motor learning differences between adults and children. Additionally, our findings support the use of both no-feedback retention and with-feedback reacquisition tests during the retention phase. The evidence for some motor learning in the children who received reduced feedback would have been missed without the use of the reacquisition (with-feedback) trials.

Cognitive effort also may be taxed by too much information. Weeks and Kordus[44] compared the effects of 100% and 33% relative frequency of knowledge of performance (KP) on learning as 11- to 14-year-old boys learned to throw a ball to specific targets. Both groups had KR provided through target information (ie, did the throw result in an accurate target hit?) in addition to the KP that included verbal information about 8 different aspects of their movement pattern. In their study, 100% KR with 100% KP was less effective in promoting throwing accuracy than in the group that received KP information on one third of the trials. Thus, the detrimental effects of 100% KR and 100% KP would suggest that too much information about both outcome and movement interfered with motor learning. Further work is needed to understand the optimization of feedback and practice in children; however, studies such as that of Weeks and Kordus and the current study reflect the need for further motor learning studies in children.

Potential Limitations

Because this was a preliminary study, the sample size was small. However, we were able to demonstrate robust differences between groups, as indicated by our significant group differences and moderate effect sizes during the no-feedback retention test for accuracy between the children groups (effect size=0.63) and consistency for both the children groups (effect size=0.76) and the adult groups (effect size=0.51). In addition, this preliminary study demonstrates the feasibility of conducting a lab-based experimental study of motor learning in children. Several colleagues, both with and without pediatric experience, questioned whether children would participate or remain engaged in a non–real-world task such as ours that included 200 practice trials. Contrary to these concerns, we were able to recruit children and their parents to participate, and all children completed both the acquisition and retention phases of the study.

An alternative interpretation of our results is that feedback withdrawal during practice may have affected the motivation of the children who received reduced feedback, causing their performance and learning to deteriorate. Although we did not assess motivation in this experiment, our findings suggest that the children who received reduced feedback did demonstrate evidence of learning. They were able to reduce their errors during the acquisition phase. They also performed as well as the children who received 100% feedback during the reacquisition phase when feedback was reintroduced, although their performance on the no-feedback retention test was significantly poorer compared with the children who received 100% feedback. In addition, there were no significant differences between the adults and children on the reported scores on the visual analog scale of perceived task difficulty, which indicates that the children in the reduced feedback group did not perceive the task to be more difficult than the other participants. Anecdotally, all of the children were very highly motivated during the acquisition test and were eager to come back the next day for the retention test. However, future studies should be planned to account for motivational influences on skill acquisition in children.

A potential limitation is the wide age range that was included in our study. There may be some developmental differences in cognitive capabilities between 8- and 14-year-old children that could be a potential confounding factor in interpreting our results. However, a *post hoc* analysis comparing the 8- and 9-year-old children and the 13- and 14-year-old children revealed that the older children had less error during the acquisition and retention tests than the younger children. Furthermore, the effects of reduced feedback frequency were similar in both age subgroups. For both younger and older children, reduced feedback frequency attenuated the performance on the retention test.

The experimental task we used in this study is not a substitute for real-world tasks; however, experimental tasks with the motor learning design used here provide a more systematic investigation of motor learning differences between children and adults. This may limit the direct application regarding the use of feedback during practice demonstrated in our study to a real-world skill in a clinical environment. However, our findings suggest that therapists should take into consideration cognitive effort when designing a training program to develop functional skills in children. Our findings also indicate that direct application of motor learning principles from adults to children should be questioned.

Clinical Implications

Our findings provide insight related to motor skill acquisition in children that may have implications for physical rehabilitation. We demonstrated that reduced relative frequency of feedback across 200 trials of practice that benefited motor learning in adults was not as beneficial in promoting motor learning in children. It is conceivable that reducing feedback frequency increases cognitive effort for the learner because, when feedback is withdrawn, the learner needs to attend to and interpret the intrinsic feedback that leads to a stronger internal representation of the skill. This increase in cognitive effort provides an optimal challenge for adults, thereby fostering motor learning. However, increased cognitive effort beyond the optimal challenge point may interfere with the learner's capability to most effectively learn a motor skill.

We used the comparison of adults with children in this motor learning study to demonstrate that information-processing capability may be a factor that affects the challenge point because it is established that children and adults have different information-processing capabilities. Our results indicate that, compared with adults, children may require more practice trials with feedback in order to form a more accurate and stable internal representation of a motor skill. Conversely, we demonstrated that children do benefit from reduced feedback (ie, reacquisition performance), but may require extended practice with reduced feedback in order to promote motor learning. Although more research is needed in this area, therapists should be aware of cognitive effort during learning of new motor tasks in children and provide additional practice with feedback if challenge during skill learning appears too high.

This is the first controlled study of feedback scheduling during practice demonstrating differences in motor skill acquisition and learning in children compared with adults. Our finding that children use feedback during practice in a different manner than adults brings into question the generalizability of motor learning studies derived from young adults to other populations. This study provides insights into the optimal scheduling of feedback during practice and suggests that feedback frequency may interact with the information-processing capability of the learner. Therefore, we expect that children, especially children with developmental brain damage such as cerebral palsy, may require longer periods of practice, with feedback reduced in a more gradual manner, to realize optimal motor learning benefits. Nevertheless, the present findings also provide insight into how cognitive effort during practice may influence motor skill acquisition, a critical cornerstone for effective motor learning in rehabilitation.

All authors provided concept/idea/research design and consultation (including review of manuscript before submission). Dr Sullivan and Mr Kantak provided writing, data analysis, and project management. Mr Kantak provided data collection and subjects. Dr Sullivan provided facilities/equipment and institutional liaisons.

The protocol was approved by the Institutional Review Board of the University of Southern California.

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