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Motor memory in childhood: Early expression of consolidation phase gains

Lilach Ashtamker [a,*], Avi Karni [a,b]

[a] The Lab of Human Brain & Learning the Department of Human Biology, University of Haifa, Haifa, Israel
[b] The Sagol Department of Neurobiology & Ethology, University of Haifa, Haifa, Israel

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ABSTRACT

Are children faster than adults in consolidating procedural knowledge? In adults, the expression of the full benefits of motor practice requires a few hours of consolidation and sleep. Here we show that, although the processes generating the delayed gains continued beyond the first few hours post-training, children expressed significant gains as early as 1 h post-training, in the awake state.

1. Introduction

There is good evidence for highly efficient skill learning and procedural memory consolidation in adults (Brashers-Krug, Shadmehr, & Bizzi, 1996; Fischer, Hallschmid, Elsner, & Born, 2002; Karni et al., 1995; Walker, 2005) and in laboratory settings children were not superior to adults in acquiring motor skill (Dorfberger, Adi-Japha, & Karni, 2007; Savion-Lemieux, Bailey, & Penhune, 2009; Wilhelm, Diekelmann, & Born, 2008). Children were, however, found to be less susceptible to interference by a subsequent task, compared to adolescents (Dorfberger et al., 2007); the latter showing the adult pattern of susceptibility (Brashers-Krug et al., 1996; Walker, 2005). Also, unlike adults, children may be able to consolidate motor memory even when time-in-sleep is not afforded (Wilhelm et al., 2008). Taken together, these findings suggest the hypothesis that maturation does not necessarily result in a reduced potential for practice-driven learning per se in puberty, but rather that the difference between children and adults may reside in the time-course of the memory consolidation phase; memory consolidation processes may be more rapid in pre-pubertal children. Studies of motor (Korman, Raz, Flash, & Karni, 2003) as well as perceptual skill learning (Ari-Even, Kishon-Rabin, Hildesheimer, & Karni, 2005; Karni & Sagi, 1993) have shown that, in adults, in addition to the improvement of performance that occurs within the practice session, additional robust gains in performance can emerge after the termination of the training session. The delayed expression of performance gains was ascribed to latent memory consolidation processes whereby improved neuronal representations of the trained task are established and presumably, structural synaptic changes are completed (Ari-Even et al., 2005; Brashers-Krug et al., 1996; Hess & Donoghue, 1994; Kleim et al., 2003; Xu et al., 2009). In human adults, delayed (‘offline’) gains are expressed not earlier than a few hours after the termination of training (Ari-Even et al., 2005; Karni & Sagi, 1993; Korman et al., 2007). Here, we directly examined the notion of rapid memory consolidation in childhood by measuring the time-course of expression of delayed gains in children. We hypothesized that delayed performance gains are expressed much earlier in children, reflecting faster memory consolidation processes.

2. Methods

Thirty children (10.6 ± 0.62 years old (mean ± SD)) took part in the study. The experiment was approved by the University of Haifa Ethics committee and the Ministry of Education, and informed parental and child consent were obtained. All children were trained in the Finger-to-thumb Opposition Sequence (FOS) learning task (Dorfberger et al., 2007; Karni et al., 1995; Korman et al., 2003) (Fig. 1a) and underwent an identical training experience with performance tested before (Pre) and immediately after (Imm-Post) the training session, as well as at 24 h post-training (24 hPost) (Fig. 1b). Before training and before each test, participants were asked to demonstrate the assigned sequence; if an error occurred the sequence was re-demonstrated by the experimenter and the process repeated as needed until the participant was able

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* Corresponding author.
E-mail address: lilach_ad@walla.co.il (L. Ashtamker).

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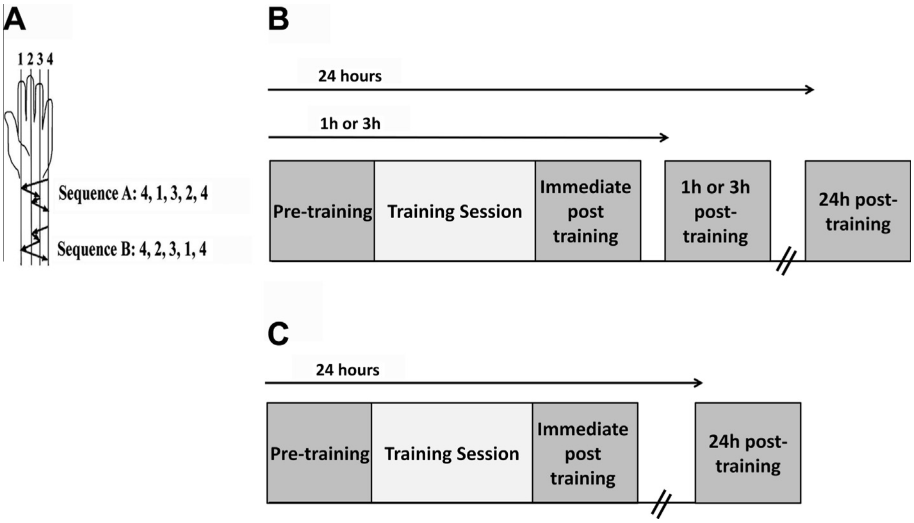

Fig. 1. Task and study design. (A) The Finger-to-thumb Opposition Sequence (FOS) learning task. (B) Four video-recorded tests were conducted on two successive days. All tests included 4 blocks (30 s each, 30 s interval) in which the FOS was tapped repeatedly "as fast and accurately as possible". (C) Study design for the control group – three video-recorded tests were conducted on two successive days. All tests included 4 blocks (30 s each, 30 s interval) in which the FOS was tapped repeatedly "as fast and accurately as possible".

to complete the sequence, correctly, four times in a row. Training included 10 blocks of trials, each requiring 16 cued repetitions of the assigned sequence. Cuing for the initiation of each sequence repetition was auditory. An interval of 2.5 s was afforded for completion of the movement sequence. There was a mandatory 30 s interval between blocks. Testing constituted four blocks, 30 s each, with a 30 s interval between blocks. In the testing blocks participants were instructed to tap the movement sequence continuously until given a stop signal. The initiation and termination of each training and testing block was cued by distinct auditory signals. Half the children ($N = 15$; age 10.4 ± 0.51 years (mean ± SD); Fig. 1b) were retested 1 h post-training (1 hPost) for delayed performance gains while the rest of the children ($N = 15$; age 10.28 ± 1.88 years (mean ± SD); Fig. 1b) were retested 3 h after the termination of training (3 hPost). A control group of 10 children (age 9.83 ± 0.72 years (mean ± SD); Fig. 1c) was run without any intermediate re-testing to show that the expression of delayed gains in performance at 24 hPost was not dependent on the 1/3 hPost tests. 12 young adults (23.17 ± 3.88 years old (mean ± SD)) were trained in an identical training protocol (Fig. 1a) and underwent testing before and immediately after training and at 1 ($n = 6$) or 3 ($n = 6$) hours post-training (1/3 hPost) as well as overnight at 24 h post-training (24 hPost).

3. Results

A repeated measure ANOVA with four Time-points (Pre, ImmPost, 1/3 hPost, 24 hPost) and Blocks (4 test blocks at each time-point) as within subject factors, with the time-of-test Group (1 or 3 h post-training test) as a between subject factor, showed significant gains in performance across the four Time-points for both speed ($F_{(3,30)} = 172.906$, $p = 0.000$) and accuracy ($F_{(3,30)} = 6.009$, $p = 0.001$). No significant differences were found between Groups, i.e., in the performance of children tested 1 h or 3 h post-training in either speed ($F_{(1,30)} = 0.234$, $p = 0.63$) or accuracy ($F_{(1,30)} = 0.019$, $p = 0.89$). There was also no significant Time-points × Group interaction. All children robustly improved their speed of performance within the training session ($F_{(1,30)} = 131.5$, $p = 0.000$) (Fig. 2A). These gains in speed were not at the cost of accuracy ($F_{(1,30)} = 0.024$, $p = 0.87$) (Fig. 2C). Moreover, a repeated measures ANOVA with two Time-points (ImmPost, 24 hPost) and Blocks (4 test blocks at each time-point) as within subject factors, showed that additional, delayed, gains in performance speed and accuracy were expressed at 24 h post-training compared to performance immediately after training (speed: $F_{(1,30)} = 118.98$, $p = 0.000$; accuracy: $F_{(1,30)} = 9.622$, $p = 0.004$). However, delayed gains in performance (rm-ANOVA with two Time-points (ImmPost, 1/3 hPost) and Blocks (4 test blocks at each time-point)) were expressed already as early as 1 h and 3 h post-training for both measures of performance, speed ($F_{(1,30)} = 48.99$, $p = 0.000$) and accuracy ($F_{(1,30)} = 5.781$, $p = 0.023$). A similar analysis was used to test the performance gains in the interval between 1/3 hPost and 24 hPost. There were significant gains in both speed ($F_{(1,30)} = 53.82$, $p = 0.000$) and accuracy ($F_{(1,30)} = 4.45$, $p = 0.038$). Fig. 3 presents the individual gains in performance among the children from the 1 hPost and the 3 hPost groups. The gains attained during by the 1 hPost test and the 3 hPost test were on average 48.31% and 45.74% of the delayed gains in performance expressed at 24 hPost-training, respectively, indicating that the processes generating the delayed gains continued beyond the first few hours post-training.

The expression of delayed gains at 24 hPost was not dependent on the test at 1/3 hPost. The control group ($N = 10$) of children run without any intermediate re-testing expressed significant delayed gains at 24 hPost (compared to performance at ImmPost; $F_{(1,10)} = 10.81$, $p = 0.009$; $F_{(1,10)} = 27.22$, p = 0.001 delayed gains in speed and accuracy, respectively) (Fig. 2B, D). These gains were comparable to those attained by 24 hPost in the 1/3 hPost groups ($F_{(1,42)} = 1.171$, $p = 0.321$; $F_{(1,42)} = 0.967$, $p = 0.389$ delayed gains in speed and accuracy, respectively).

In the young adults, control group, there were robust delayed gains in both speed and accuracy expressed in the 24 hPost test, but not in the 1/3 hPost tests (Fig. 4). A rm-ANOVA with four Time-points (Pre, ImmPost, 1/3 hPost, 24 hPost) and four Blocks as within subject factors and Group (1 hPost, 3 hPost) as between subjects factor, showed a significant main effect of Time-points (speed: $F_{(3,12)} = 202.73$, $p = 0.000$; accuracy: $F_{(3,12)} = 20.18$, $p = 0.000$) but no significant Group effect. There was a significant Group × Time-points interaction for performance speed ($F_{(1,12)} = 5.21$, $p = 0.005$), indicating that the rate of improvement between tests was different for the two test-time conditions. A post hoc exploration indicated that the difference was due to the