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Limits on movement integration in children: The concatenation of trained subsequences into composite sequences as a specific experience-triggered skill

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ABSTRACT

Complex movement sequences may be easier to acquire in sub-segments. Nevertheless, the neuro-behavioral constraints on assembling short multi-element movement segments, acquired piecemeal and serially, into larger, composite units of action, are not clear. Here we examined the ability of children to combine movement subsequences into longer, composite, sequences. Eleven-year-olds were trained in the performance of two, 3-elements, finger-to-thumb opposition movement sequences and were tested, overnight, in the performance of composite, 6-elements, sequences. Two experiments were compared, differing only in whether or not a brief test for integration into a composite sequence was afforded immediately post-training. This composite sequence (Full) was a direct forward integration of the two subsequences, maintaining the order in which the two subsequences were trained. In both experiments, overnight performance of movement elements within the composite sequences was better than naive performance, but slower and less accurate compared to the performance of the identical movement elements in the context of the trained subsequences. Integration was as effective in the Full sequence as when the order between subsequences was switched (Reversed). However, the early test for subsequence integration was critical in inducing clear between-session ('offline') gains, as expressed in overnight performance, in both the Full and Reversed sequences. Without this brief experience in integration, no overnight gains were expressed in any of the 6-elements sequences. Moreover, the immediate post-training test resulted in a relative advantage of the Full and Reversed sequences over a 6-element sequence in which the order of the elements was mirror-reversed within each subsequence. Thus, training on subsequences may not spontaneously lead to an advantage in the performance of composite sequences, in children. However, an early brief experience with a composite sequence can suffice to trigger the establishment and consolidation of an integration routine. This routine is specific for the order of movement within the trained subsequences, but not for the order in which the subsequences were practiced.

1. Introduction

Practice on a sequence of movements can lead to the organization of a series of movement elements into segments that appear to be treated as a single unit (motor chunks, specific sequences) (e.g., Karni et al., 1995, 1998; Korman, Raz, Flash, & Karni, 2003; Park & Shea, 2005; Rozanov, Keren, & Karni, 2010; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, 1994, 2010). Moreover, when a sequence is composed of a relatively large number of elements (over 4–5 movements) learners can chunk elements into independent subsequences (e.g., Povel & Collard, 1982; Rosenbaum, Kenny, & Derr, 1983; Seidler, 2006; Verwey, 1994; Verwey & Eikelboom, 2003). The formation of motor chunks has been described as a fundamental strategy used to facilitate the performance of complex serial behaviors and is considered central to motor learning (Sakai et al., 2003; Verwey & Eikelboom, 2003) although different chunks can be created by different persons for a given sequence of movements (Sakai et al., 2003). The spontaneous segmentation indicates that there are limitations to the number of elements that can be represented in a single motor chunk (Povel & Collard, 1982; Verwey, Lammens, & van Honk, 2002; Wilde, Magnuson, & Shea, 2005).

However, the finding of spontaneous chunking does not necessarily indicate that learning by practice on smaller chunks may be advantageous compared to training on whole, longer, but well

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organized movement sequences (Anderson, 1968; Cunningham, 1971; Fontana, Mazzardo, Furtado, & Gallagher, 2009; McGeoch & Irion, 1952; Stahl & Miller, 1989; Wrightman & Lintern, 1985). Notions such as complexity theory suggest that the learning of complex tasks may not necessarily benefit from experience with sub-elements of the task, and that exposure to a complex but highly organized experience may be superior as a learning experience compared to serial piecemeal experience with subsequences and parts, in generating skill (Cohen & Sekular, 2010; Ebbinghaus, 1913; Goodman, 1986; Hansen, Tremblay, & Elliott, 2005; Naylor & Briggs, 1963; Schmidt & Wrisberg, 2008). Thus, while several studies suggest that learners can consolidate motor sequences that consist of more than 5 elements, given intensive practice (Panzer & Shea, 2008; Park & Shea, 2005; Park, Wilde, & Shea, 2004; Sakai et al., 2003; Wilde & Shea, 2006), there is evidence supporting the notion that motor learning is faster when chunks of previous movement sequences can be incorporated into new ones (Sakai et al., 2003).

One potential disadvantage in training a movement sequence as distinct subsequences is that of interference. Studies in young adults (Brashers-Krug, Shadmehr, & Bizzi, 1996; Walker, 2005) have shown that when learning a new movement sequence, and within a time window of a few hours, a second, different movement sequence is presented, the latter sequence is consolidated while the former sequence does not show delayed gains in performance (interference effect). These studies have suggested that the order of learning is crucial for creating a long-term memory for motor sequences. However, studies have shown that children (pre-adolescents) were less susceptible to this form of interference (Dorfberger, Adi-Japha, & Karni, 2007), even without the affordance of time in sleep (Ashtamker & Karni, 2013). Thus, it may be the case that complex movement sequences may be easier to acquire in sub-segments in children (Ruitenberg, Abrahamse, & Verwey, 2013). Nevertheless, the neuro-behavioral constraints on assembling short multi-element movement segments, acquired piecemeal and serially, into larger, composite units of action, are not clear.

The Finger Opposition Sequence (FOS) learning task has been extensively used as a paradigm in both behavioral and brain imaging studies for studying the acquisition and establishment of long term motor memory (e.g., Ashtamker & Karni, 2013; Fischer, Hallschmid, Elsner, & Born, 2002; Karni et al., 1995, 1998; Korman et al., 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; Adi-Japha, Badir, Dorfberger, & Karni, 2014; Dorfberger et al., 2007). FOS learning has been studied in children (Ashtamker & Karni, 2013; Dorfberger et al., 2007) and has been used to delineate distinct phases in the acquisition of motor skill (procedural knowledge). Two of these characteristic phases have been referred to as, (i) 'fast' learning – manifest as rapid performance improvements within the training session (within-session, 'online' gains), and (ii) 'slow' learning, reflected in performance gains that can be expressed hours after the termination of the training session (between-sessions, delayed 'offline' gains) (Ashtamker & Karni, 2013; Hauptmann & Karni, 2002; Karni et al., 1998; Korman et al., 2003; Maquet, Schwartz, Passingham, & Frith, 2003; Stickgold et al., 1998). Delayed gains in performance presumably reflect the successful termination of consolidation processes; once consolidated the representation of the movement sequence is believed to be resistant to interference, and to become easily retrievable despite long periods of time without additional training (e.g., Ashtamker & Karni, 2013; Hauptmann & Karni, 2002; Karni, 1996; Karni et al., 1995, 1998; Korman et al., 2003). Importantly, the resulting skill is largely sequence specific. Both adults and children, were able to fully express these gains in performance only for the trained sequence, i.e., when the component movements were arranged in the order in which they were practiced; there was little transfer to the performance of movement sequences composed of the same elements but in a different order (Dorfberger, Adi-Japha, & Karni, 2012; Karni et al., 1998; Korman et al., 2007; Rozanov et al., 2010).

Here we tested the ability of children, 9–12 year olds, to concatenate two short finger opposition subsequences into longer, composite, sequences, a day after a session of training on the two subsequences (using a protocol that was shown effective in triggering procedural memory consolidation processes in this age-group). We hypothesize that integration abilities will be limited (i.e., there will be a cost when executing the integrated sequences, in terms of performance speed and accuracy) unless participants are afforded some experience with the longer, composite sequences immediately following training. We further conjectured that higher integration costs will be incurred when the order of movements within the subsequences will be altered.

2. Methods

2.1. Participants

25 right handed children (10.96 ± 0.147 years old (AVG ± SE); 14 girls) took part in the study. 12 children participated in Experiment 1 (10.92 ± 0.193 years old (AVG ± SE); 7 girls), and 13 children participated in Experiment 2 (11 ± 0.226 years old (AVG ± SE); 7 girls). Informed parental and child consents were obtained. All children were asked to respond to a general health questioner and reported on good general health with no medical conditions that could impair fine motor performance, no history of neurological, musculo-skeletal or developmental disorders, no chronic illness which requires medication, and no diagnosis of developmental learning disabilities or attention deficit disorder (ADHD). All children reported at least 8 h of sleep per night – with no recognized sleep problems and no diagnosed sleep–wake cycle disruptions. The experiment was approved by the University of Haifa Ethics committee and the Ministry of Education. Participants were asked to respond to a hand dominance questionnaire (Oldfield, 1971) and a sleep assessment questionnaire (Horne & Ostberg, 1976).

2.2. Task

All children were trained in the Finger-to-thumb Opposition Sequence (FOS) learning task (Fig. 1A) using the protocol of Ashtamker and Karni (2013), but with training afforded on two 3-element subsequences. There were four 3-element subsequences (for training and testing) and three 6-element sequences were used to test integration abilities (Fig. 1A). Subsequences A_1 and B_2 were mirror reversed to each other in the order of elements, as was the case for A_2 and B_1. The subsequences were designed in this manner to equalize difficulty: studies have shown that 5-element mirror reversed sequences are of equal difficulty in young adults and in children, but training on one does not well-generalize to the performance of the other (Ashtamker & Karni, 2013; Dorfberger et al., 2007; Korman et al., 2003, 2007). All training and testing sessions were conducted during school day, i.e., between 8:00 and 13:30. All children underwent an identical training experience with performance tested before (Pre) and immediately after (ImmPost) the training session, as well as at 24 h post-training (24hPost) (Fig. 1B and C). At the beginning of the experiment (before the Pre test), participants were given explicit instruction and a demonstration of the movements composing each subsequence, by the experimenter. Before training and before each test, participants were asked to produce the assigned sequence, correctly, four times in a row; if an error occurred the sequence was re-demonstrated by