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Sequential motor skill in preadolescent children: The development of automaticity

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ABSTRACT

This study investigated to what extent preadolescent children, like young adults, learn to perform sequential movements in an automatic fashion. A sample of 24 children (mean age = 11.3 years) practiced fixed 3-key and 6-key sequences in the discrete sequence production task by responding to key-specific stimuli via spatially compatible key presses. We compared their performance with that of 24 young adults (mean age = 22.0 years). Results showed that performance improved with practice for both age groups, although children were generally slower. Compared with young adults, children had less explicit knowledge but relied more on the available explicit knowledge when executing familiar 6-key sequences. Furthermore, they completed fewer of these sequences on the basis of just the first stimulus and showed a slower transition between successive segments within the sequences. Together, these findings provide insight into the degree to which preadolescent children develop automaticity in sequential motor skill, suggesting that preadolescent children automatize the processes underlying longer movement sequences slower and/or to a lesser extent than is the case with young adults. The current study is in line with the idea that there are several mechanisms that underlie sequencing skill and suggests that the use of these mechanisms may be dependent on age.

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Introduction

Most complex motor actions that people perform (e.g., driving a car, lacing one's shoes) consist of a series of simpler movements that are executed in a specific order. The overall relevance of such sequential motor skills in everyday life prompts questions about skilled performance across the lifespan. The current study contributes by exploring sequential motor skill in preadolescent children and comparing this with such skill in young adults. In contrast to more basic motor skills such as pointing (e.g., Badan, Hauert, & Mounoud, 2000), reaching (e.g., Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998), and aiming (e.g., Smits-Engelsman, Sugden, & Duysens, 2006), few studies have addressed fine motor skills such as sequential finger movements in children. Moreover, studies that examined such sequencing skill have typically addressed only the development of implicit (i.e., incidental) sequence learning. These studies typically showed that both children and adults improve with practice on the learned sequence but that children are typically slower (e.g., Dorfberger, Adi-Japha, & Karni, 2007, 2012; Gabbard, Caçola, & Bobbio, 2011; Savion-Lemieux, Bailey, & Penhune, 2009; Thomas & Nelson, 2001; Thomas et al., 2004). However, little is known about children's performance on the execution of brief discrete series of key presses that allow for strong open-loop control and the mechanisms underlying such performance.

Discrete movement sequences are assumed to be the building blocks of more complex sequential actions that are present in our everyday behavior. For example, making a cup of coffee builds from movement sequences that underlie reaching for the cup, turning on the tap, and putting in the filter. The so-called discrete sequence production (DSP) task is representative of the way such movement sequences are acquired and controlled, and it allows for the fast development of sequencing skill in a relatively controlled manner (for more detailed discussions, see Abrahamse, Ruitenberg, De Kleine, & Verwey, 2013; Rhodes, Bullock, Verwey, Averbeck, & Page, 2004; Verwey, Abrahamse, & De Kleine, 2010). The DSP task typically involves the sequential display of two series of up to seven stimuli in a fixed order that each require a response by means of a spatially compatible key press. Because the fixed keying sequences have a recognizable beginning and end, and a response-to-stimulus interval of 0 ms, the DSP task allows the development of automated movements in the form of *motor chunks*, which are brief series of successive responses that are represented in a single memory representation and can be prepared in advance and executed at high pace. The development of motor chunks results in large benefits in terms of speed of responding (sometimes average response latencies are observed at <100 ms for key presses after the first) and in the relative independence from key-specific stimuli after the first stimulus (i.e., open-loop control)—the first stimulus being used for sequence selection. More complex sequences are organized by using more abstract, higher level action representations, including several motor chunks.

In the current study, we examined whether preadolescent children, like young adults, show indications for automaticity in sequencing skill after practicing discrete keying sequences. We refer to automaticity in sequencing skill as performance that is largely on motor chunk use controlled by an autonomous motor processor. We elaborate on this below (cf. Verwey, Abrahamse, De Kleine, & Ruitenberg, 2013; Verwey et al., 2010). Earlier studies explored the development of automaticity in children with respect to gross motor skills such as running (Whitall, 1991) and reaching (Kuhtz-Buschbeck et al., 1998) and also in more cognitive tasks such as number processing (Girelli, Lucangeli, & Butterworth, 2000) and word processing (Spironelli & Angrilli, 2009). By and large, these studies demonstrated that the development of automaticity is limited in children compared with adults. The current study aimed to further contribute to the literature on automaticity in children by focusing specifically on fine motor sequencing skills.

Automaticity in fine sequential motor skill

Research with the DSP task led to the dual processor model of sequencing skill (Verwey, 2001; see also Abrahamse et al., 2013). This model assumes that two distinct processors are active in discrete sequence skills: a cognitive processor and a motor processor. The relative contribution of these processors to sequencing performance changes with practice, resulting in distinct modes of sequence execution. When initially performing a motor sequence in the DSP task, the sequence is said to be executed in the so-called *reaction mode*. In this mode, each key press of the sequence is executed in isolation from other key presses; the cognitive processor is responsible for the translation of each key-specific stimulus into the appropriate response (i.e., S–R translation), whereas the motor processor generates each actual response.

After extensive practice, execution may shift to the *chunking mode* in which a movement sequence is executed as one or more motor chunks. In the chunking mode, there is no longer a need for selecting, preparing, and separately executing all individual elements of the sequence. The actual skill has developed and sequencing is automatic to the extent that the whole sequence can be executed based on the first stimulus (which signals the sequence that should be executed). At this stage, the cognitive processor selects motor chunks and loads them into a temporary motor buffer, from which the motor processor then executes these motor chunks in a relatively automatic—that is, autonomous—fashion (i.e., without the need for cognitive involvement once initiated). The latter renders performance relatively independent of awareness of the motor chunk elements that are executed.

It is typically assumed that the capacity of motor chunks is limited to approximately three to five key presses (e.g., Bo & Seidler, 2009; Sakai, Kitaguchi, & Hikosaka, 2003; Verwey, Abrahamse, & Jiménez, 2009; Verwey & Eikelboom, 2003), indicating that longer sequences are represented by multiple motor chunks. Indeed, after extensive practice, longer sequences typically include one (or more in the case of still longer sequences) slowly executed key press(es) somewhere halfway through the sequence, and this is assumed to reflect retrieval and initiation of an upcoming motor chunk within the sequence. Interestingly, even though one would intuitively attribute these retrieval and initiation processes during sequences execution to the cognitive processor, Verwey and colleagues (2010) demonstrated that—after substantial practice—the transition between motor chunks is relatively unaffected by a secondary task. This suggests that the transition from one motor chunk to the other *within a fixed sequence* can automatize with practice. This may indicate hierarchical control of longer sequences and is probably highly dependent on the consistency with which motor chunks succeed each other.

Finally, the dual processor model includes one additional feature that is relevant here. Although in the chunking mode the cognitive processor is assumed to load entire motor chunks into a motor buffer—which are then executed by the motor processor—the cognitive processor can also engage in S–R translations for each individual key press within a motor chunk to assist the relatively fast motor processor. This leads for each key press to a race between two response selection processes (with a response being executed as soon as one of these processes is completed) and results in the fastest possible responses (as supported by the notion of statistical facilitation; Verwey, 2001). Moreover, recent research suggests that—in the absence of external stimuli—the cognitive processor can also use explicit sequence knowledge to elicit responses in parallel with the motor processor (Ruitenberg, Abrahamse, De Kleine, & Verwey, 2012). However, the contribution of explicit knowledge is likely to reduce as motor chunks develop because sequence representations become more automatic and thus dominant (Cleeremans & Jiménez, 2002) and also because less time is available to process explicit knowledge during sequence execution at more advanced skill levels (Verwey et al., 2010).

Overall, the dual processor model explains in detail how sequential movements can become highly automatized. Besides the highly automatized execution of motor chunks by an autonomous motor processor, even the transition from one motor chunk to the next may become automatized with practice. This leaves the major part of non-automatized processes to take place before or during the execution of the first key press.

The current study

To examine the development of automaticity in sequential motor skill in preadolescent children (mean age = 11.3 years, range = 10.6–13.2), we employed the DSP task in which we had participants practice 3-key and 6-key sequences. Given the reduced information processing speed and working memory capacity of children (e.g., Kail, 1991, 2000), we anticipated that they would benefit from dividing the longer 6-key sequences into shorter segments. Such a benefit of practicing longer action sequences in parts first has earlier been shown to enhance sequence learning (e.g., Park, Wilde, & Shea, 2004). Therefore, half of the participants in each age group practiced the 6-key sequence, with a pause halfway through the sequence to induce segmentation into two 3-key segments.

After the practice phase, participants performed a test phase that involved three conditions (cf. Verwey, 2010; Verwey, Abrahamse, Ruitenberg, Jiménez, & De Kleine, 2011). In the familiar condition, participants performed their practiced 3-key and 6-key sequences in response to key-specific stimuli. In the unfamiliar condition, participants carried out unfamiliar 3-key and 6-key sequences, again in response to key-specific stimuli. Finally, in the single-stimulus condition, participants were asked to produce their practiced 3-key and 6-key sequences in response to just the first stimulus of each sequence. In this block, thus, participants could not rely on external guidance by the stimuli.

We expected preadolescent children to show sequence-specific performance gains, just like young adults. These gains would be indicated by faster execution of familiar sequences than of unfamiliar sequences in the test phase. In addition, the difference between the first key press of a sequence and the subsequent key presses was expected to be larger for familiar sequences than for unfamiliar sequences. We further hypothesized—based on earlier studies—that children are generally slower and less accurate than young adults (cf. Dorfberger et al., 2007, 2012; Gabbard et al., 2011; Savion-Lemieux et al., 2009; Thomas & Nelson, 2001; Thomas et al., 2004). The question remains, however, whether preadolescents show similar development of automaticity as young adults. To this purpose, we performed more detailed analyses.

As discussed above, the dual processor model predicts a gradual development of automaticity in sequencing performance as practice evolves. We used four indicators to determine to what extent children, like young adults, develop such automaticity. A first indicator for automaticity is the rapid execution of familiar sequences resulting from performance being predominantly controlled by the autonomous motor processor executing motor chunks. Using motor chunks would allow for responses that are faster than would be expected on the basis of typical S–R translations—as is the case in a typical choice reaction time task and when performing unfamiliar sequences. Second, as the relative contribution of the motor processor increases over time (paralleled by a gradually reduced involvement of the cognitive processor), automaticity is expected to be indicated by a decreasing use of explicit knowledge with practice. Consequently, a correlation between scores on an explicit knowledge test and execution rate of the familiar sequences—specifically for the first few responses of a sequence (Verwey & Abrahamse, 2012)—is expected only as long as the involvement of the cognitive processor is high but should approach zero when automaticity develops. A third indicator for automaticity is that sequences can be performed based on just the first stimulus of that sequence, which suffices for sequence selection and preparation. In the case of automatization, thus, participants should be able to correctly perform their sequences in the single-stimulus condition—and without large drops in performance speed. Fourth, we investigated whether segmentation (i.e., dividing a sequence into multiple shorter segments, e.g., motor chunks) would be observed in the unstructured sequence, and we examined the transition between these spontaneously created segments within a sequence. The transition process of one motor chunk to the next has been found to become highly automated—and thus fast—with practice in young adults (Verwey et al., 2010, 2013). As a fourth indicator for automaticity, therefore, we inspected this transition process for both age groups.

Method

Participants

Participants were 24 preadolescent children (11 male and 13 female) between 10.6 and 13.2 years of age[1] (mean age = 11.3 years). Prior to the study, children's parents or guardians received an information letter that explained the nature and procedure of the study, and they gave their passive informed consent on the participation of their children. The data of the preadolescents were compared with those of 24 young adults (8 male and 16 female, mean age = 22.0 years, range = 18.4–29.9) who gave their

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[1] Although the age range of the preadolescent children may seem relatively large, this group involved only one 10-year-old and one 13-year-old. Removing these two participants from the analyses did not yield a different pattern of results.

informed consent prior to the study. The study was approved by the ethics committee of the Faculty of Behavioral Sciences at the University of Twente. Children and young adults were tested at their school and in our laboratory, respectively.

Apparatus

Stimulus presentation, timing, and data registration were controlled by E-Prime 2.0 software. The program ran on a Pentium IV computer with all unnecessary Windows XP services switched off to allow accurate time measurement. The task was performed on a standard desktop computer keyboard.

Task and procedure

At the start of the experiment, participants received written instructions regarding the task, which was orally extended by the experimenter if participants had any questions. Participants placed their left and right ring, middle, and index fingers on the d, f, g, j, k, and l keys of a computer keyboard. Six black horizontally aligned square stimulus placeholders were displayed against a white background. Between the third and fourth placeholders, a small gap appeared with the letter "H" in the middle to mimic the keyboard layout. When a placeholder was filled with green, participants depressed the spatially corresponding key. Directly after pressing the correct key, the next stimulus in the sequence was presented by filling another placeholder with green.

Each participant performed two sequences. Participants were presented with one sequence of three stimuli (S_1–S_3) and one sequence of six stimuli (S_1–S_6). Correctly pressing the corresponding keys resulted in a fixed 3-key sequence of responses R_1–R_3 and a fixed 6-key sequence of responses R_1–R_6. The time between onset of the presentation of a stimulus and the response to that stimulus is indicated by T_n (e.g., T_2 denotes the response time to the second stimulus, S_2, in a sequence).

Before each sequence, the six empty placeholders were presented for 1000 ms, after which the first stimulus of the sequence was displayed. Directly after depressing the correct key, the next stimulus of the sequence appeared. Following a correctly executed sequence, the display was erased white for 2000 ms to indicate completion of the sequence. Pressing a false key resulted in an error message for 500 ms. The ongoing sequence was then aborted and followed by a 1000-ms empty screen, after which the next sequence started.

For half of the participants, the 6-key sequence in the practice phase contained a pause between R_3 and S_4 (i.e., the *prestructured group*) to impose a segmentation structure onto the sequence (e.g., Verwey, 1996). This pause consisted of a non-aging interval of at least 300 ms (with a maximum of 2000 ms), preventing participants from gradually increasing their expectation for the next stimulus as the interval lasts longer (Gottsdanker, Perkins, & Aftab, 1986). Importantly, the pause was removed in the test phase. For the other half of the participants in each age group, their 6-key sequence did not include a pause and, thus, the next stimulus of a sequence was presented as soon as the correct key was depressed (i.e., the *unstructured group*).

Across all participants, keys (and thus fingers) were counterbalanced across sequential positions so that each of the six fingers on the keyboard contributed as much to the response times at each sequential position. For example, one participant practiced the sequences KFGDJL and FKL, the next participant practiced LGJFKD and GLD, and so on. Participants practiced their sequences during six practice blocks. Each block included the presentation (in random order) of 24 3-key sequences and 24 6-key sequences. In total, thus, participants practiced each sequence 144 times. Halfway through each block, there was a pause of 40 s. At the end of each block, a participant's mean reaction time and error percentage were displayed. Before starting the next block, there was a rest period of 4 min.

After the practice phase, participants filled out the awareness questionnaire so that their explicit knowledge of the sequences could be assessed. In the recall test, participants were asked to write down the sequences they had practiced by using the letters of the keys they had pressed during the experiment. The positions of the six keys on the keyboard (including the "H" marked in the center position) were printed in the questionnaire as a reminder of the keyboard layout. In the recognition test, participants were asked to select their 6-key sequence from a list of 12 alternatives and their 3-key sequence from another list of 12 alternatives.

In the test phase, participants completed three blocks that each involved a distinct experimental condition. In the *familiar condition*, the same key-specific stimuli were presented to participants as in the practice phase. In the *single-stimulus condition*, only the first stimulus of a familiar sequence was presented, after which each key press was followed by the concurrent filling of all placeholders. When a key was pressed, the placeholders briefly turned white and then were filled with green again. The *unfamiliar condition* involved the presentation of one new 3-key sequence and one new 6-key sequence. The order of the three test blocks was counterbalanced across participants, and the blocks were separated by a 40-s pause. All blocks involved the presentation (in random order) of 12 trials of both the 3-key and 6-key sequences. As in the practice phase, an error message was displayed when a false key was pressed, and the sequence was then aborted. After completion of each block, participants were shown their mean reaction times and error percentages. The duration of the experiment was approximately 1 h.

Data analysis

We calculated mean response times (RTs) per key press for the prestructured and unstructured sequences for every participant in each block of the practice and test phases. RT was defined as the time between stimulus presentation and depression of the appropriate response key. Sequences in which one or more errors had been made were omitted from the RT analyses, with 5% and 13% of the sequences being omitted on average for the young adults and preadolescent children, respectively. This is within the typical range for DSP task studies (cf. De Kleine & Verwey, 2009; Verwey, 1999, 2010; Verwey et al., 2011). These error percentages are separately described, analyzed, and interpreted in more detail below in the Results and discussion sections. In addition, sequences were omitted from the RT analyses when the total execution time exceeded more than 2.5 standard deviations from the mean across participants in a particular age group. This was done separately for the 3-key and 6-key sequences per block in the practice phase, and per condition in the test phase, and resulted in the removal of less than 1% of the sequences.

For the practice phase, RTs of the 3-key and 6-key sequences were subjected to separate mixed factorial analyses of variance (ANOVAs), with block (6) and key position within the sequence (3 or 6, hereafter referred to as key) as repeated measures and age group (2: children or young adults) as a between-participant variable. For the 6-key sequences, pause (2: pause between R_3 and S_4 or no pause) was an additional between-participant variable. Analysis of RTs in the test phase also involved ANOVAs on RTs of the familiar and unfamiliar 3-key and 6-key sequences, but in the single-stimulus condition the number of correctly produced sequences was our main variable of interest. When appropriate, planned comparisons were performed to specifically address our hypotheses stated above in the Introduction. Finally, proportions of errors were calculated for every participant. For the practice phase, this was done per block for each key press of the 3-key and 6-key sequences. In the test phase, we calculated proportions of errors for each key press of the 3-key and 6-key sequences per condition. The error data were then subjected to ANOVAs in a similar way as the RT data.

Results and discussion

Practice phase

For the 3-key sequence, results of the Age Group (2) × Block (6) × Key (3) ANOVA showed that preadolescent children were generally slower than young adults (432 vs. 259 ms), $F(1, 46) = 57.01$, $p < .001$, $\eta_p^2 = .55$. Fig. 1 shows that mean RTs decreased across blocks, $F(5, 230) = 126.70$, $p < .001$, $\eta_p^2 = .73$, but this reduction did not differ between the age groups ($p > .28$). A main effect of key showed that RTs decreased with key position in the sequence, $F(2, 92) = 106.18$, $p < .001$, $\eta_p^2 = .69$. Furthermore, a Key × Block interaction was indicative of an increasing T_1 versus T_2T_3 difference across blocks, $F(10, 460) = 38.11$, $p < .001$, $\eta_p^2 = .45$. Planned comparisons confirmed that in both age groups the T_1 versus T_2T_3 difference increased across Blocks 1 to 6, $Fs(1, 46) > 69.84$, $ps < .001$, $\eta_p^2s > .60$. The increase did not differ between the groups ($p = .14$).

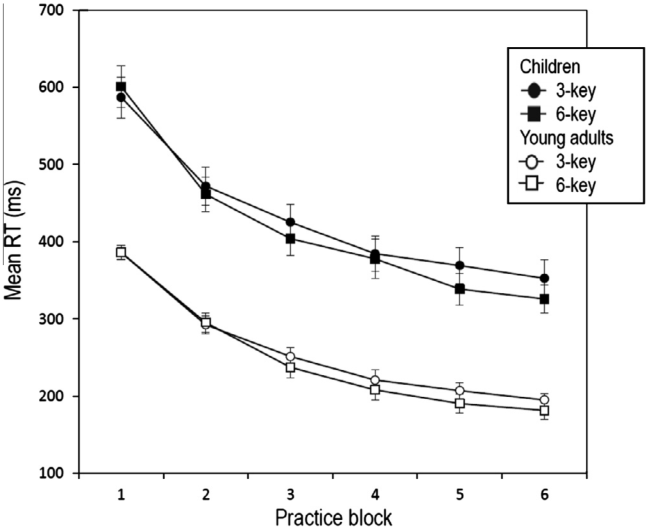

Fig. 1. Mean RTs across all responses within the 3-key and 6-key sequences per practice block as a function of age group. Error bars represent standard errors.

Results of the 6-key sequence version of the above ANOVA—now including the between-participant pause (2) variable—again showed that children were slower than young adults (418 vs. 250 ms), $F(1, 44) = 52.93$, $p < .001$, $\eta_p^2 = .54$. A Key × Pause interaction indicated that key presses differed between the prestructured and unstructured groups, $F(5, 220) = 3.59$, $p < .01$, $\eta_p^2 = .08$. Planned comparisons confirmed our expectation that the difference between T_4 and other key presses within the sequence was larger in the prestructured sequence than in the unstructured sequence, $F(1, 44) = 12.58$, $p < .001$, $\eta_p^2 = .22$, which is in line with the idea that participants in the prestructured group segmented their sequence systematically at the position of the pause. Fig. 1 shows that mean RTs decreased across blocks, $F(5, 220) = 206.27$, $p < .001$, $\eta_p^2 = .82$, and a Block × Age interaction suggested that this reduction was larger for the children than for the adults (275 vs. 205 ms), $F(5, 220) = 4.02$, $p < .05$, $\eta_p^2 = .08$. An additional Block × Key × Age interaction, $F(25, 1100) = 2.91$, $p < .01$, $\eta_p^2 = .06$, suggested that the difference between T_1 and the mean of $T_{2\text{–}6}$ developed differently over blocks for the children and the young adults. This seems to be caused mainly by an initial difference between the age groups in Block 1 (T_1 vs. $T_{2\text{–}6}$ differences = −10 ms for children and 87 ms for young adults), whereas in the final practice block this difference between T_1 and $T_{2\text{–}6}$ was similar for both age groups (261 ms for children vs. 277 ms for young adults, $p = .19$).

Previous studies have shown that in unstructured sequences segmentation patterns differ across participants and that individual differences may be concealed when individual RTs are averaged over participants (e.g., Bo & Seidler, 2009; Kennerley, Sakai, & Rushworth, 2004; Verwey, 2003; Verwey & Eikelboom, 2003; Verwey et al., 2009). To examine whether such individual segmentation patterns were present in the final practice block, we determined transition points for each participant who practiced the unstructured sequence. A transition point was defined as a key press that was significantly longer than both its preceding and succeeding key presses (cf. Bo & Seidler, 2009; Kennerley et al., 2004). For every participant, we performed one-tailed paired *t* tests ($p < .05$) on RTs of the third, fourth, and fifth key presses of each sequence to evaluate whether they could be classified as a transition point. The first, second, and sixth key presses were not included in the analysis because we assumed that the first key press was always the beginning of the first segment and that the second and sixth key presses were always within the first or last segments. Transition points were found for 10 participants (five in each age group), indicative of sequence segmentation. Interestingly, as Fig. 2 shows, the difference between the transition points and other key presses within a sequence (not

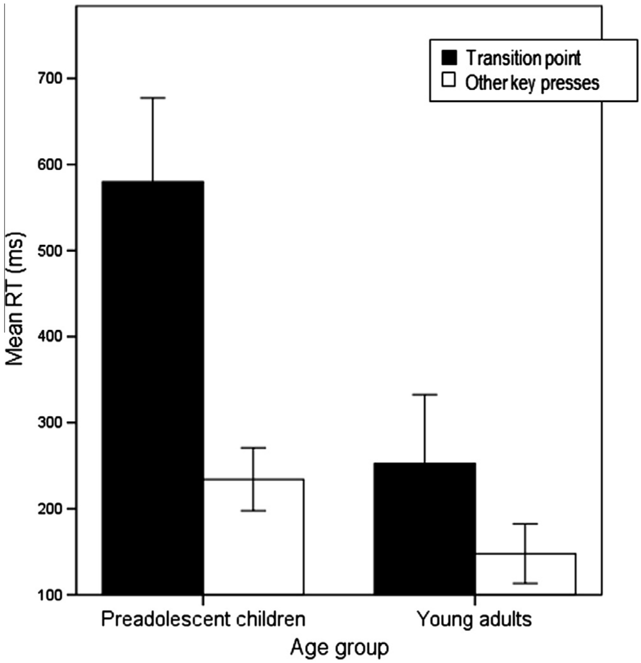

Fig. 2. Mean RTs of the transition point and other key presses (not including T_1) in the unstructured 6-key sequences in final practice block per age group. Error bars represent standard errors.

including T_1) was much larger for the children than for the young adults (346 vs. 105 ms), $t(8) = 2.20$, $p < .05$, $d = 1.55$. This suggests that the spontaneous transition between two segments of a sequence is slower in children, possibly due to the inability to automatize this process.

Finally, error percentages per key position within the 3-key and 6-key sequences were analyzed via Age Group (2) × Block (6) × Key (3) and Age Group (2) × Block (6) × Key (6) × Pause (2) ANOVAs, respectively. Results showed that mean error percentages per key were similar for preadolescents and young adults (3.1% vs. 2.2% for the 3-key sequence, $p = .12$, and 3.0% vs. 2.1% for the 6-key sequence, $p = .09$). The 3-key ANOVA further showed a main effect of key, $F(2, 92) = 30.99$, $p < .001$, $\eta_p^2 = .40$, which interacted with age group, $F(2, 92) = 8.53$, $p < .01$, $\eta_p^2 = .16$, indicating that preadolescents' errors differed more between keys (1.5% vs. 5.6% vs. 2.2% for R_1, R_2, and R_3, respectively) than those of young adults (0.3% vs. 3.1% vs. 3.3%, respectively).

In summary, the results of the practice phase showed that children were generally slower at executing their sequences than young adults. There was no indication for a speed–accuracy trade-off given that children also made more errors in absolute terms. As hypothesized, sequencing performance improved with practice in both age groups, as indicated by the RT decrease across the practice blocks as well as an increase in the difference between the first and subsequent key presses of a sequence with practice. Analysis of individual differences in segmentation patterns of the unstructured sequence suggested that the transition between successive segments in that sequence was slower for children than for young adults.

Test phase

Familiar and unfamiliar sequences

Mean RTs of the 3-key sequence were analyzed with a mixed Age Group (2) × Familiarity (2: familiar or unfamiliar sequence) × Key (3) ANOVA. Fig. 3 shows that children were generally slower than

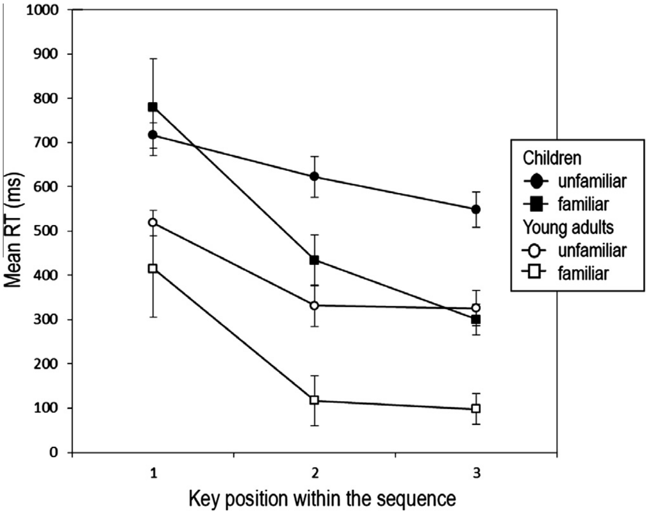

Fig. 3. Mean RTs per key position in the familiar and unfamiliar 3-key sequences in the test phase per age group. Error bars represent standard errors.

young adults (567 vs. 301 ms), $F(1, 46) = 19.94$, $p < .001$, $\eta_p^2 = .30$. In addition, RTs decreased with key position in the sequence, $F(2, 92) = 58.26$, $p < .001$, $\eta_p^2 = .56$. The familiar sequences were executed faster than the unfamiliar sequences (357 vs. 511 ms), $F(1, 46) = 22.18$, $p < .001$, $\eta_p^2 = .33$. Furthermore, a Key × Familiarity interaction supported the notion that the difference between T_1 and T_2T_3 was larger for the familiar sequences than for the unfamiliar sequences, $F(2, 92) = 6.98$, $p < .01$, $\eta_p^2 = .13$. Planned comparisons confirmed sequence-specific performance gains for both age groups, with the T_1 versus T_2T_3 difference being larger in the familiar sequences than in the unfamiliar sequences, $Fs(1, 46) > 9.39$, $ps < .001$, $\eta_p^2s > .17$. Performance gains were similar in both age groups ($p = .30$).

Fig. 4 shows the mean RTs of the 6-key sequences. Results of a mixed Age Group (2) × Familiarity (2) × Key (6) × Pause (2) ANOVA once again showed that children were slower than adults (536 vs.

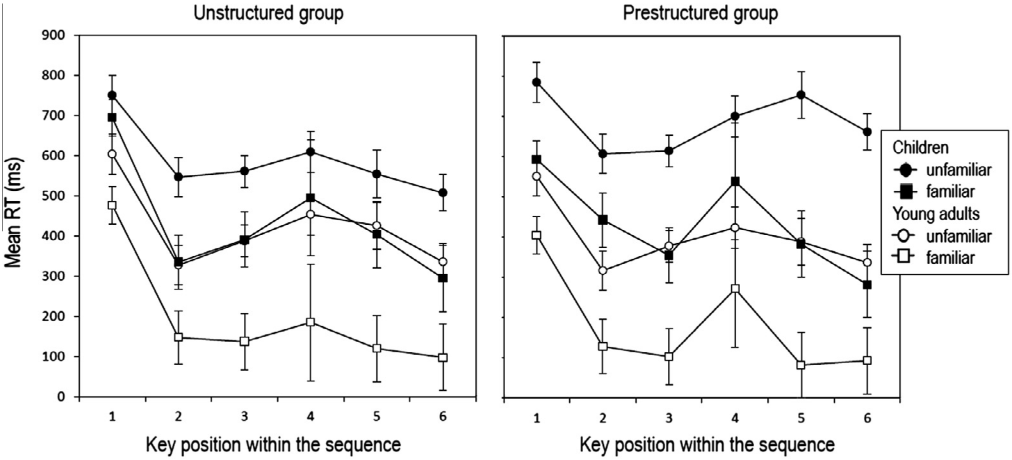

Fig. 4. Mean RTs per key position in the familiar and unfamiliar 6-key sequences for the prestructured and unstructured groups in the test phase per age group. Error bars represent standard errors.

299 ms), $F(1, 44) = 23.70$, $p < .001$, $\eta_p^2 = .35$, and that familiar sequences were executed faster than unfamiliar sequences (311 vs. 524 ms), $F(1, 44) = 43.77$, $p < .001$, $\eta_p^2 = .50$. A Key × Familiarity interaction was in line with the notion from Fig. 4 that the difference between T_1 and $T_{2–6}$ was larger in the familiar sequences than in the unfamiliar sequences, $F(5, 220) = 3.61$, $p < .01$, $\eta_p^2 = .08$, and planned comparisons further confirmed that this applied to both age groups, Fs(1, 44) > 14.72, ps < .001, η_p^2s > .25. There was no difference between the age groups in this respect ($p = .79$).

As expected, planned comparisons showed that in both prestructured age groups, T_4 was longer than $T_2T_3T_5T_6$, Fs(1, 44) > 4.25, ps < .05, η_p^2s > .09. This suggests that the sequence was indeed systematically divided into two separated 3-key segments. For each age group, the T_4 versus $T_2T_3T_5T_6$ difference was larger in the familiar sequences than in the unfamiliar sequences, Fs(1, 44) > 38.52, ps < .001, η_p^2s > .47. There were no differences between the two age groups (ps > .45).

Error percentages of the 3-key and 6-key sequences were submitted to an Age Group (2) × Familiarity (2) × Key (3) ANOVA and an Age Group (2) × Familiarity (2) × Key (6) × Pause (2) ANOVA, respectively. Results showed that error percentages were generally higher for the preadolescents than for the young adults in the 3-key sequence (4.6% vs. 2.1%), $F(1, 46) = 5.69$, $p < .05$, $\eta_p^2 = .11$, but not in the 6-key sequence (5.3% vs. 4.6%, $p = .54$). The 3-key ANOVA further showed a main effect of key, $F(2, 92) = 5.88$, $p < .01$, $\eta_p^2 = .11$, which interacted with age group, $F(2, 92) = 3.30$, $p < .05$, $\eta_p^2 = .07$, indicating that the preadolescents' errors differed more between keys (3.8% vs. 7.0% vs. 3.0% for R_1, R_2, and R_3, respectively) than those of the young adults (0.7% vs. 2.8% vs. 2.8%, respectively). Results of the 6-key ANOVA showed that error percentages were lower in the familiar condition than in the unfamiliar condition (3.4% vs. 6.5%), $F(1, 44) = 18.42$, $p < .001$, $\eta_p^2 = .29$. As in the 3-key ANOVA, results showed a main effect of key, $F(5, 220) = 10.69$, $p < .001$, $\eta_p^2 = .19$, with errors increasing from R_1 to R_4 (1.0% to 8.5%) and then decreasing again to R_6 (3.9%).

In summary, the results showed that in both age groups the difference between the first key press of a sequence and the subsequent key presses was larger for familiar sequences than for unfamiliar sequences. Both age groups showed a relatively slow response at T_4 in the familiar prestructured sequence when the pause was removed, confirming that the pause had induced a transition point for both children and young adults on this position in the sequence.

Single-stimulus condition

For the single-stimulus condition, the variable of main interest was the number of correctly performed sequences. Fig. 5 suggests that children depended more on external stimuli for the execution of familiar sequences than young adults in that they executed fewer sequences correctly in the single-stimulus condition. A Kruskal–Wallis ANOVA showed that the number of correctly executed 3-key sequences did not differ for preadolescents and young adults ($p = .65$). However, a similar ANOVA confirmed that the number of correctly executed 6-key sequences was lower for the preadolescents than for the young adults, $H(1) = 8.35$, $p < .01$, $r = .42$.

To analyze the RTs across participants who executed their 3-key sequence at least once in the single-stimulus condition (22 children and 24 young adults), we performed an Age Group (2) × Test Condition (3: familiar vs. unfamiliar vs. single-stimulus) × Key (3) ANOVA. Results showed that children were generally slower across the conditions than young adults (627 vs. 295 ms), $F(1, 44) = 30.72$, $p < .001$, $\eta_p^2 = .41$. A Key × Test Condition × Age Group interaction, $F(4, 176) = 4.07$, $p < .05$, $\eta_p^2 = .09$, suggested that the RT patterns of individual key presses differed between the sequence conditions for the children and the young adults. RTs of both the children and young adults decreased with key position in the sequence in the familiar and unfamiliar conditions. However, whereas RTs of young adults showed a similar pattern in the single-stimulus condition, children's RTs in this condition actually increased from T_1 to T_2 and then decreased sharply again to T_3. This suggests that the children quickly responded to the first stimulus but then needed to identify and prepare the sequence, resulting in a slower second key press, whereas young adults were able to do so during the first key press. The 6-key version of the above ANOVA also showed that the 16 children who had executed at least one sequence in the single-stimulus condition correctly were slower than the 24 young adults (503 vs. 296 ms), $F(1, 38) = 23.94$, $p < .001$, $\eta_p^2 = .39$. Results further showed a Test Condition × Age Group interaction, $F(2, 72) = 3.68$, $p = .05$, $\eta_p^2 = .09$, suggesting that the RT difference between age groups varied across the test conditions. Detailed analysis showed that although preadolescents were generally

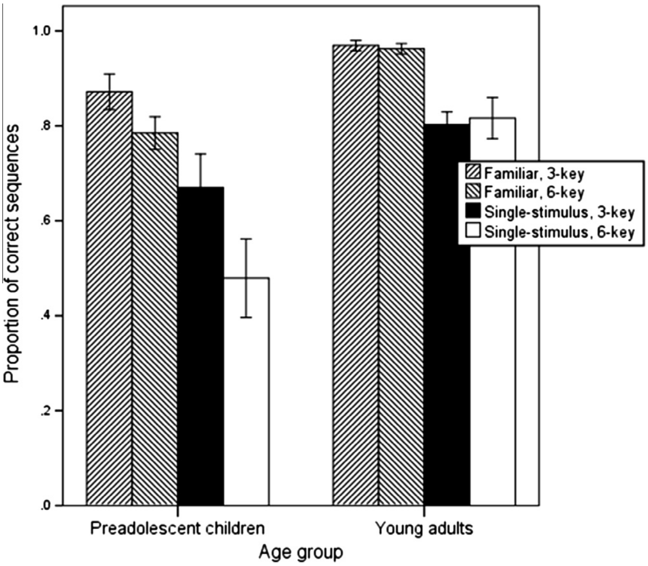

Fig. 5. Mean proportions of correctly executed sequences per age group in the familiar and single-stimulus conditions of the test phase as a function of sequence length. Error bars represent standard errors.

slower than young adults, the difference between age groups was larger in the single-stimulus condition than in the familiar condition (326 vs. 173 ms), $F(1, 36) = 7.07$, $p < .05$, $\eta_p^2 = .16$.

In summary, children executed fewer 6-key sequences correctly in the single-stimulus condition than young adults, suggesting that they had relied more on the external stimuli for the execution of this sequence in the familiar condition. The number of correctly executed 3-key sequences did not differ between age groups. Children who were able to correctly execute at least one sequence in the single-stimulus condition did so more slowly than the young adults. For the 6-key sequence, this difference between age groups was larger than that in the familiar condition.

Explicit sequence knowledge

Analyses of the awareness questionnaire showed that fewer children than young adults correctly wrote down their 3-key sequence, $\chi^2(1) = 9.60$, $p < .01$, $\varphi = .45$ (see Table 1). There was no difference between the age groups in recall of the 6-key sequence ($p = .24$). Young adults were better at recognizing both their 3-key and 6-key sequences from a set of 12 alternatives, χ^2s$(1) > 4.00$, ps $< .05$, φs $> .29$. Overall, children seem to have had less explicit knowledge of their familiar sequences than young adults.

Table 1
Numbers and corresponding percentages of participants (out of 2 × 24) who correctly wrote down the familiar sequences immediately following the practice phase ("Recall" columns) and recognized their sequences from sets of 12 alternatives ("Recognition" columns).

	Recall		Recognition	
	3-Key	6-Key	3-Key	6-Key
Preadolescent children	16 (67)	12 (50)	15 (63)	15 (63)
Young adults	24 (100)	16 (67)	24 (100)	21 (88)

Note: Percentages are in parentheses.

We examined whether execution of the first three responses of the familiar sequences correlated with explicit knowledge (i.e., number of correctly recalled sequences). Because RTs are known to decrease rapidly from the first response to ensuing responses in familiar sequences, and awareness is involved mainly in the first few responses, we calculated for each participant the T_1 versus T_2T_3 difference for the 3-key and 6-key sequences. For the 3-key sequence, this difference did not correlate with explicit knowledge of that sequence in either age group ($ps > .14$). For the 6-key sequence, the T_1 versus T_2T_3 difference correlated with explicit knowledge of that sequence for the preadolescents, $r(24) = .53$, $p < .01$, but not for young adults ($p > .14$). When analyzing performance in the single-stimulus condition, results showed that for children the T_1 versus T_2T_3 difference in both the 3-key and 6-key sequences correlated with explicit knowledge of those sequences, $rs(22) > .42$, $ps < .05$. For young adults, however, correlations were not significant ($ps > .43$). Thus, it seems that children make more use of their explicit knowledge for sequencing performance than young adults.

Developmental differences

Although the main goal of the current work was to investigate to what extent preadolescent children, like young adults, learn to perform motor sequences in an automated fashion, we also examined whether there were developmental differences in sequencing performance within the group of preadolescents. To that end, we compared the sequencing performance of 10- and 11-year-olds ($n = 16$) with that of 12- and 13-year-olds ($n = 8$). Results of ANOVAs on RTs in the 3-key and 6-key sequences in the familiar and unfamiliar test conditions showed no differences between these two groups ($ps > .11$). In addition, the number of correctly performed 3-key and 6-key sequences did not differ between the groups for any of the test conditions ($ps > .32$). The groups did not differ in the amount of explicit knowledge in that recall and recognition of both the 3-key and 6-key sequences were similar for both groups ($ps > .22$). Overall, then, no indications were found that our group of preadolescent children was heterogeneous in nature with respect to sequence performance. Still, future studies should explicitly address this issue.

General discussion

The current study examined to what extent preadolescent children, like young adults, perform 3-key and 6-key sequences in the DSP task in an automatic fashion. As predicted on the basis of previous studies (cf. Dorfberger et al., 2007, 2012; Gabbard et al., 2011; Savion-Lemieux et al., 2009; Thomas & Nelson, 2001; Thomas et al., 2004), the results demonstrated that both age groups showed sequence-specific performance gains, with familiar sequences being executed faster than unfamiliar sequences and the difference between the first key press and subsequent key presses being larger for familiar sequences than for unfamiliar sequences. The first impression that derives from the RT data (Figs. 3 and 4) is that the preadolescents perform very similar to the young adults, although they are generally slower (and no indications for a speed–accuracy trade-off were observed, with children also producing more errors overall). However, we actually believe that the overall slowing is characteristic of a slower and/or limited development of automaticity in preadolescents as compared with young adults, and this notion is supported by marked differences between the two age groups across three additional indicators for automaticity in motor sequences. Below we elaborate on this.

First, rapid execution of particular key presses (i.e., the ones after chunk initiation), an indication of automatization (Verwey, 2010), was less pronounced in preadolescent children than in young adults. That is, the children always remained much slower than the young adults, and responses beyond the first remained within the range of what could be expected for a typical choice RT task in which performance remains based on S–R translations. For example, in a study by Thomas and Nelson (2001), 10-year-old children performed a key press task with spatially corresponding S–R mapping and showed average RTs of approximately 400 ms when stimuli were presented in a random order. Similarly, a group of 13-year-old children (the control group) in the study by Deroost et al. (2010) also showed average RTs of approximately 450 ms under such conditions (i.e., the random blocks of the sequence learning task). From the notion that motor chunking would be expected to generate equally fast responses for children and adults, the slower performance in preadolescents may be interpreted as performance remaining largely dependent on the workings of a (well-trained) cognitive processor (possibly including advance preparation of future key presses based on sequence knowledge) that selects and loads single key presses into the buffer of the motor processor—as opposed to motor chunks as with young adults.

Second, this suggestion is supported by the influence of explicit knowledge during sequence execution—a feature that is assumed to be typical of a dominant cognitive processor and that does not fit well with the notion of motor chunking. For both the familiar and single-stimulus conditions of the test phase, we observed that for preadolescent children—but not for young adults[2]—the difference in RT between the first and second/third key presses was correlated with explicit sequence knowledge (with the exception of the 3-key sequence in the familiar condition); children with more awareness showed a larger difference. According to the dual processor model, the difference should not be related to explicit knowledge when performance is based on the cognitive processor loading a motor chunk (i.e., representing a series of key presses) into a motor buffer that is subsequently executed by the motor processor as if it were a single response (Verwey et al., 2010). Hence, as a second indication from this study, preadolescents seem to remain more reliant on explicit knowledge for sequence execution than young adults—which fits the notion that their performance remains largely dependent on the effortful processes of the cognitive processor (i.e., loading and executing key presses one by one) for a longer time than in the case of young adults. This is further corroborated by the observation that error percentages of the 3-key sequence showed more variation for preadolescents than for young adults both in the practice phase and in the familiar test condition. Because performance based on motor chunks executed by the motor processor would predict relatively stable error percentages *within* such an integrated representation (cf. Rosenbaum, Kenny, & Derr, 1983), the relatively large variation in preadolescents fits better with the notion that their performance was based largely on the cognitive processor selecting and loading single key presses.

Third, we examined whether preadolescent children and young adults could perform their sequences without the guidance of external stimuli in the single-stimulus condition. Previous studies have shown that young adults are quite good at this, and from the dual processor model it could be predicted that this is due to motor chunking (and thus automatization); the need for actively using stimuli decreases with practice due to the motor processor autonomously executing motor chunks, and the first stimulus of a sequence suffices for proper preparation and execution of that sequence. The current results show that the number of correctly performed 3-key sequences was similar for both age groups. However, compared with young adults, children completed fewer 6-key sequences correctly in the single-stimulus condition. This suggests that they depend more on external stimuli—that is, on the direct one-by-one S–R translation processes of the cognitive processor—for the execution of this sequence, whereas young adults could enhance performance in the single-stimulus condition through relying on their motor chunks. Moreover, whereas the drop in RT in young adults was relatively small in the single-stimulus condition, children showed larger RT drops and even seemed to use different RT patterns for sequence execution in the single-stimulus condition than in the familiar condition. This further suggests that children used stimulus information across the whole sequence in the practice phase and the familiar test block and did not engage in motor chunking.

Fourth, we observed that children who segmented their unstructured sequence needed more time for the transition from one segment to the next compared with young adults. This suggests that the transition between sequence segments is not as quickly automated as it is in young adults (Verwey et al., 2010, 2013). However, in the prestructured sequence, this transition did not differ between age groups, suggesting that children benefit from prestructured sequences in that the artificial presegmentation results in smoother (and possibly more automatic) transitions between segments.

Altogether, these findings suggest that preadolescent children automatize the processes underlying (especially longer) movement sequences to a lesser extent than is the case for young adults. It seems

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[2] The absence of a significant correlation between explicit knowledge and execution of the 3-key sequence in the familiar and single-stimulus conditions for young adults may reflect a ceiling effect because all of the young adults correctly recalled the sequence. We thank an anonymous reviewer for this suggestion. However, this reasoning does not apply to the 6-key sequence because one third of the young adults were unable to recall the sequence.

that for children the cognitive processor (and S–R translation) remains dominant in sequence execution even after substantial practice, whereas for young adults the motor processor (and motor chunking) gradually takes over control with this same amount of practice. It may be suggested that cognitive processor efforts in preadolescents are based on explicit sequence knowledge given that awareness was related to the difference between the first and following key presses of a sequence. In addition, the observation that children completed fewer 6-key sequences in the single-stimulus condition suggests that the cognitive processor continues to be engaged in S–R translations. One could even argue that the cognitive processor uses explicit knowledge in the beginning of the sequence and then switches to S–R translations later in the sequence as explicit knowledge of later key presses does not come to mind as readily. Detailed inspection of the awareness questionnaire indeed showed that of the 12 children who could not reproduce all elements of their 6-key sequence correctly, two recalled none of the sequence elements. The remaining 10 children reproduced at least the first element correctly up to a maximum of four successive correctly recalled sequence elements. Finally, we should point out that the notion that sequencing performance in children—but not in young adults—strongly relies on explicit knowledge was recently supported by Weiermann and Meier (2012). They demonstrated that children's sequencing performance in an implicit sequence learning task was largely conditional on the development of explicit knowledge, with little indication for purely implicit sequence learning in children. These findings are in line with the current results that sequencing performance remains more cognitively controlled—and less automated—in preadolescents than is the case for young adults.

The differential degree of automaticity in sequential movement skill between preadolescent children and young adults could be related to the involvement of brain structures that may still be maturing in children. During the learning of new motor sequences in young adults, the prefrontal cortex and cerebellum are activated (Doyon & Benali, 2005; Jueptner, Frith, Brooks, Frackowiak, & Passingham, 1997; Jueptner, Stephan, et al., 1997). These areas are mainly responsible for the generation of quick and accurate responses (Hikosaka et al., 1999). The basal ganglia are also involved in sequential motor skill (Doyon & Benali, 2005; Jueptner, Stephan, et al., 1997). Besides their role in the acquisition of new sequences, they are involved in motor chunking (Boyd et al., 2009; Graybiel, 1998; Hayes, Davidson, Keele, & Rafal, 1998; Penhune & Steele, 2012; Sakai et al., 2003; Tremblay et al., 2010) and may be involved—in close interaction with the prefrontal cortex—in the initiation of individual motor chunks of familiar sequences (Verwey, Lammens & van Honk 2002; Wymbs, Bassett, Mucha, Porter, & Grafton, 2012).

From these three main structures, the basal ganglia are thought to mature relatively early compared with the prefrontal cortex and cerebellum (Diamond, 2000; Sowell, Delis, Stiles, & Jernigan, 2001; Sowell, Trauner, Gamst, & Jernigan, 2002; Østby et al., 2009). More specifically, the basal ganglia have been found to change relatively little in people between 8 and 30 years of age (e.g., Østby et al., 2009), whereas prefrontal areas and the cerebellum are known to still develop well into adolescence (e.g., Sowell et al., 2001, 2002). Wymbs and colleagues (2012) recently showed that a frontoparietal network may be involved in the explicit segmentation of movement sequences. It could be speculated that preadolescent children are less efficient in the stable segmentation of their sequences and that this results in slower development of motor chunks. However, in the prestructured sequence, the segmentation pattern was induced by means of a pause halfway through the sequence, and although this should have facilitated stable segmentation, we still did not observe the performance rate one would expect on the basis of motor chunking. Another possibility is that the use of motor chunks—rather than the development of such chunks—differs between the two age groups in the current study. Specifically, the study of Verwey (2003) indicates that the initiation of motor chunks is an intentional and goal-directed process, and it may be that these processes—which are among others related to the prefrontal cortex—are less developed and/or efficient in preadolescents. Admittedly, however, these ideas are highly speculative, and future studies are required to clarify the link with brain structures.

Finally, along with developmental changes in the brain, there are also age-related changes in cognitive abilities. For example, information processing speed (e.g., Kail, 1991, 2000) and working memory capacity (which is related to the prefrontal cortex; e.g., Luciana & Nelson, 1998) are less developed in children than in adults. These factors have been found to be interrelated in that developmental changes in processing speed have been found to mediate the increase of working memory capacity with age (Fry & Hale, 1996). Various studies have suggested that working memory is related to chunking (Bo, Borza, & Seidler, 2009; Bo & Seidler, 2009; Verwey, 1999, 2010; Verwey et al., 2011). Verwey (1999) proposed that the motor buffer, in which (elements of) motor chunks are loaded before execution, can be viewed as a part of working memory. This may imply that the loading of the motor buffer is less efficient when working memory capacity is limited, which could explain slower transitions between segments of longer sequences in preadolescent children.

In conclusion, the current findings suggest that preadolescent children automatize the execution of longer movement sequences to a lesser extent than young adults. Although both age groups show sequence-specific performance gains with practice, we argue that the relative contributions to sequencing skill of the cognitive and motor processors differ. In preadolescents the cognitive processor seems to remain dominant in the execution of longer movement sequences, whereas in young adults practice leads to clear motor chunking that is dominated by an autonomous motor processor. In all, the current findings are in line with the notion that there are several mechanisms that underlie the execution of familiar movement sequences and suggest that the relative contribution of these mechanisms may depend on age. Future studies should validate these ideas within other paradigms and zoom in on developmental changes with respect to automaticity in sequential motor skill.

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