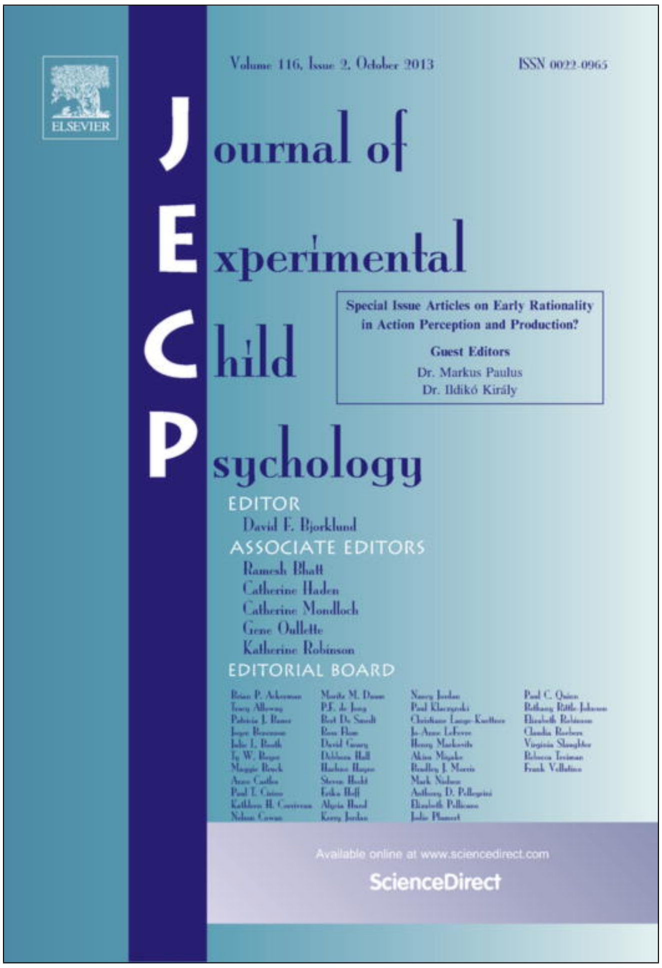
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Age-related differences in perceptuomotor procedural learning in children

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A B S T R A C T

Procedural learning is generally considered to proceed in a series of phases, with cognitive resources playing an important role during the initial step. From a developmental perspective, little is known about the development of procedural learning or the role played by explicit cognitive processes during learning. The main objectives of this study were (a) to determine whether procedural learning performance improves with age by comparing groups of 7-year-old children, 10-year-old children, and adults and (b) to investigate the role played by executive functions during the acquisition in these three age groups. The 76 participants were assessed on a computerized adaptation of the mirror tracing paradigm. Results revealed that the youngest children had more difficulty in adapting to the task (they were slower and committed more errors at the beginning of the learning process) than 10-year-olds, but despite this age effect observed at the outset, all children improved performance across trials and transferred their skill to a different figure as well as adults. Correlational analyses showed that inhibition abilities play a key role in the performance of 10-year-olds and adults at the beginning of the learning but not in that of 7-year-olds. Overall, our results suggest that the age-related differences observed in our procedural learning task are at least partly due to the differential involvement of inhibition abilities, which may facilitate learning (so long as they are sufficiently developed) during the initial steps of the learning process; however, they would not be a necessary condition for skill learning to occur.

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Introduction

From an early age, children acquire many kinds of perceptuomotor skills; for example, they can learn how to eat with cutlery, manipulate a computer mouse, tie shoelaces, or use a variety of tools at school. Through repeated practice, these skills gradually become automated and can be performed without awareness or fatigue. They represent what one calls "routines"—that is, procedural skills. Procedural learning refers to the process in which new perceptuomotor, perceptual, or cognitive skills are acquired through long and repetitive training (Cohen & Squire, 1980; Willingham, 1998). Considering the early maturity of the brain structures underlying procedural learning, it is generally acknowledged that this system is present early in childhood and that, undoubtedly, it plays an important role in child development.

The process of learning a procedural skill is generally considered to proceed in a series of distinct learning phases, with cognitive resources playing an important role during the initial step of learning. Through repeated practice, the skill becomes progressively more automatic and the involvement of controlled cognitive functions progressively dwindles. This conception is formalized in the adaptive control of thought model (ACT model; Anderson, 1982, 2000), where knowledge is first stored in a declarative form and then converted into procedural knowledge. According to this top-down approach to learning, this transformation occurs in three stages; the first ("cognitive") stage requires a large amount of cognitive (e.g., working memory) resources, the involvement of cognitive functions is progressively reduced during the second ("associative") stage, and the last ("autonomous") stage is characterized by automation and no longer requires the involvement of explicit processes. Brain imaging studies in adults have confirmed the existence of distinct learning phases showing that different brain structures are active at the different stages in motor skill learning (Doyon & Benali, 2005; Hikosaka et al., 1999). The early stages of learning recruit the basal ganglia and cerebellum; the prefrontal, parietal, and limbic areas; and the motor cortical regions. When consolidation has occurred, performance becomes automatic and the circuits involved depend on the type of motor skill acquired (Doyon & Benali, 2005). The ACT model has received experimental support from a number of studies on perceptuomotor procedural learning that have highlighted the role of explicit cognitive processes during the first learning phase. More specifically, several studies have demonstrated that some procedural learning tasks require the intervention of nonprocedural functions, in particular executive functions. First, Kennedy, Partridge, and Raz (2008) showed that the effects of age on perceptuomotor skill acquisition (e.g., mirror tracing) may be mediated by the deterioration of cognitive resources (notably working memory) during aging. Second, Brosseau, Potvin, and Rouleau (2007) argued that the age-related difficulties observed in the learning of the mirror tracing task reflect mainly the involvement of executive functions (inhibitory control). Third, Schmidtke, Manner, Kaufmann, and Schmolck (2002) found that patients with prefrontal lesions experience some difficulties with adaptation during the initial phases of learning on the pursuit rotor task, confirming the involvement of the prefrontal cortex during the first phase of motor learning. To summarize, results obtained with adults and elderly people support the proposal that explicit cognitive processes play a key role during the first phase of procedural learning. These studies also demonstrate age-related differences in at least some procedural learning tasks where executive functions seem to play a key role.

Although the top-down approach to procedural learning (i.e., performance during the first learning stages is sustained by explicit high-level mechanisms) has received the most attention, some researchers have also proposed a bottom-up approach to skill learning, which postulates that explicit declarative knowledge is not necessarily involved in procedural skill learning and that the knowledge acquired could be stored in an implicit mode from the beginning of learning (Karmiloff-Smith, 1992; Liao & Masters, 2001; Sun, Merrill, & Peterson, 2001). Karmiloff-Smith (1992), for example, proposed the representational redescription model (RR model), which suggests that children shift progressively during development from a procedural learning mode (involving the formation of procedural knowledge) to a more declarative learning mode (leading to the formation of declarative knowledge). This view suggests the possibility that procedural learning in young children (whose explicit learning mechanisms have not yet fully developed) might work differently than the ACT model suggests without necessarily involving the intervention of explicit cognitive resources (e.g., working memory) during the first phase of learning.

The developmental literature on procedural learning is sparse; little is known about the mechanisms underlying procedural skill acquisition in children and their development or variation in developmental time. Most studies on the developmental trajectory of perceptuomotor procedural learning in children have used the serial reaction time paradigm (e.g., Karatekin, Marcus, & White, 2007; Thomas et al., 2004), which focuses specifically on the ability to detect the sequential structure in some repeated sequence of stimuli implicitly without any explicit knowledge of the information that is to be learned. This situation differs from the perceptuomotor adaptation paradigm used in many studies on procedural learning, in which there is no repeated sequential information to be learned. One perceptuomotor adaptation task that is widely used in adult studies (and particularly in neuropsychological studies) is the mirror tracing task, which requires participants to trace a shape with a pencil while seeing the action of their hand reflected in a mirror. In this task, which resembles real-life procedural learning situations in many respects, participants need to adapt their motor behavior continuously in response to distortions of visual feedback; contrary to the serial reaction time task, the learning situation can be qualified as explicit in that participants know from the outset that they need to improve their performance. Moreover, they need to inhibit an overlearned association between vision and motor behavior. In contrast to the (supposedly) "implicit" nature of the learning processes involved in the serial reaction time paradigm, it is generally acknowledged in the adult literature that explicit cognitive processes play an important role in many skill learning situations, at least during the initial phases of learning (e.g., Brosseau et al., 2007). Surprisingly, only a few developmental studies have investigated procedural learning using this kind of paradigm in children. For instance, Ferrel-Chapus, Hay, Olivier, Bard, and Fleury (2002) explored the adaptive capacities of children between 5 and 11 years of age and a group of adults. Participants needed to draw a figure without being able to see their hand and with a view of the scene that was rotated by 180°. The researchers' findings showed age-related differences in initial performance; the youngest children (5 and 7 years) had more difficulties than 9- and 11-year-olds and adults, with the 5- and 7-year-olds being more affected by the visual distortion. Interestingly, in spite of this initial difference in performance, children and adults learned at similar rates. These data raise the question of the cognitive mechanisms underlying perceptuomotor skill acquisition in children, whose explicit mechanisms are still developing.

In this context, the main purposes of this study were twofold. One goal was to determine whether procedural learning performance improves with age by comparing groups of 7-year-old children, 10-year-old children, and adults on a new perceptuomotor adaptation task; for this purpose, the transfer of the ability to a different and more complex task, as well as its long-term retention, was also explored. The second goal was to investigate the role played by executive functions during the first and last stages of the acquisition of the skill in these three groups. These age groups were chosen because they correspond to key steps in the development of executive functions (Brocki & Bohlin, 2004; Jonkman, 2006; Luciana & Nelson, 1998; Schleepen & Jonkman, 2010; Welsh, Pennington, & Groisser, 1991). According to Anderson's (2000) ACT model, and given the involvement of executive functions during the first phase of a perceptuomotor adaptation task (e.g., Brosseau et al., 2007), we expected to find executive functions to be involved mainly at the beginning of learning. Moreover, we hypothesized that executive resources would contribute less to the learning process in 7-year-olds (because these functions are less developed in these younger children) than in 10-year-olds and adults and that 7-year-olds might then have more difficulty in acquiring the procedural skill (e.g., their performance could be slower or less accurate during the first trials). Considering that some complex executive skills can develop further during adolescence (e.g., Huizinga, Dolan, & Van der Molen, 2006; Schleepen & Jonkman, 2010), we also predicted that a difference might be found between 10-year-olds and adults.

Method

Participants

In total, 76 participants divided into three age groups were assessed: a first group of 22 7-year-olds (M_{age} = 7 years 4 months [7;4], range = 7;00–7;11, 10 girls and 12 boys), a second group of 31 10-year-olds (M_{age} = 10;4, range = 10;00–10;11, 14 girls and 17 boys), and a comparison group of 23 adults (M_{age} = 25;8, range = 19;10–29;10, 13 women and 10 men).

No participants had any history of neurological or psychiatric problems or learning disabilities. All participants had normal or corrected-to-normal vision, and they were all right-handed and had already used a computer mouse. All participants performed above the fifth percentile on Raven's Progressive Matrices (Raven, 1960; Raven, Court, & Raven, 1998).

Measures

Perceptuomotor procedural learning task

The mouse task consisted in a new and original computerized test. The equipment was composed of a laptop computer (15-inch screen and 1024 × 768-pixel resolution) and an optical wireless mouse (Trust MI-4150x). The task was programmed using Toolbook software (Version 9.0).

Participants were told that they would be playing a computer game with characters from the movie *Ice Age*. To maintain a sufficient motivation level, especially in young children, the task was designed to be attractive and to resemble a video game. It required participants to trace the contour (formed by two black lines spaced 1.7 cm apart) of a geometrical shape with an inverted mouse using their dominant hand as quickly as possible. With the inverted mouse, the relationship between the movements of the mouse and the movements of the cursor was rotated by 180°; when the mouse was moved to the left or down, the cursor would move to the right or up, and vice versa. The instruction was to follow the contour of the figure as quickly and accurately as possible in order to "catch" various toys appearing on the screen (inside the contour) without leaving the limits of the contour. If the cursor moved outside the parallel lines, participants needed to reposition it at the place where it had veered off (indicated by a red square on the contour of the shape) in order to continue the task. On each trial, the time (in seconds) to trace the entire figure and the number of errors (number of times the cursor veered outside the contour) were recorded by the computer.

Before starting the experiment, participants were asked to trace a square with the normally oriented mouse. The purpose of this initial measure was to control whether, within each group, performance with the mouse (in its usual orientation) might influence performance with the inverted mouse. Immediately after this initial control measure, participants were asked to trace other geometrical shapes, this time with the inverted mouse.

Training task. Children were told that they would need to learn to use the inverted mouse by tracing the contour of the same triangle several times. The base of the triangle was 23.5 cm wide, and its height was 11.5 cm. The training task took place during the first session and consisted of four blocks of 3 trials. A short break was provided between trials, and a longer break was provided after two blocks. To keep participants motivated and focused on the task, at the end of each trial a message was displayed on the screen congratulating participants and presenting some information about the next mission (e.g., "Congratulations! Now, you must help Scrat to collect his nuts.").

Transfer task. An important aspect of procedural learning concerns the "generalization" of the learned skill (Seidler, 2007). Indeed, the ability to apply the new skill to a situation different from the one in which it was trained is an indicator that it has been actually learned (i.e., that participants did not simply learn the specific movements that needed to be performed during training). Thus, we examined the transfer of the ability to a different and more complex task and explored whether participants' performance on this transfer task remained stable after a 1-week delay. For that, participants needed to trace a five-pointed star (16.5 cm wide from one point to the opposite one) with the inverted mouse. This transfer task was performed three times: once before the training task (i.e., pretest) and two times after (i.e., posttest). The posttest was administered immediately after the training task (immediate transfer task) and during a second session following a 1-week delay in order to test long-term retention of the skill (delayed transfer task).

Executive tasks

To evaluate the impact of executive functions on the procedural learning task, participants' performance on tasks testing three core executive processes—inhibition, cognitive flexibility, and working memory (Miyake et al., 2000)—was measured.

Inhibition. We used two versions of the Simon task, one adapted from Germain and Collette (2008) for the adults and one adapted from Catale, Germain, and Meulemans (2011) for the children, in order to assess the ability to inhibit inappropriate motor responses and ignore irrelevant characteristics of perceptual stimuli (Subtests 3 and 5). All responses were given using either a left ("q") or right ("l") response key on a standard AZERTY keyboard. At the beginning of each subtest, participants were instructed to respond as quickly as possible while avoiding errors. In Subtest 3, the 80 trials involved an arrow (in the adult version) or a running dog (in the child version) appearing randomly on either the left (40 trials) or right (40 trials) side of the screen. Participants needed to ignore the location of the dog or arrow and to press the key on the side indicated by the direction of the arrow or the direction in which the dog was running. Only the data from the 40 items requiring perceptual inhibition were analyzed. In the 40 trials of Subtest 5, participants were asked to press the key that was opposite to where the centrally located arrow was pointing or the central dog was running. Inhibition scores consisted of z-scores for time on each test (Simon 3 and Simon 5).

Cognitive flexibility. All participants were also given an adaptation of a flexibility task (TAP; Zimmermann & Fimm, 2009) that assesses mental switching between two sets of targets (letters and numbers). Two stimuli, one letter and one number, are presented simultaneously on the screen, one on the left side and the other on the right side of a fixation point. Stimulus presentation is random; the letter could appear on the left side and the number on the right side or vice versa. Participants needed to press the response key ("q" or "l" on the keyboard) located on the same side as the target, which alternated on successive trials (letter–number–letter–number, etc.), as quickly as possible. The task consisted of 60 trials. When participants made an error, they were warned by an acoustic tone and given the next target stimulus. Median response times (in milliseconds) were recorded for subsequent analysis.

Working memory. Working memory was assessed using the letter–number sequencing and backward digit span tests from the Wechsler Intelligence Scale for Children–Fourth Edition (WISC-IV) (Wechsler, 2005) and Wechsler Adult Intelligence Scale–Third Edition (WAIS-III) (Wechsler, 2000). The working memory score consisted of z-scores for both of the tests.

Procedure

All participants were tested individually in a quiet room in two sessions separated by a 1-week interval. In the first session, they performed the initial control task (with the mouse in its usual orientation), the pretest measure (tracing a star with the inverted mouse), the procedural training task (tracing a triangle with the inverted mouse, comprising four blocks of 3 trials), and the posttest (i.e., immediate transfer task). The second session comprised the second posttest (i.e., delayed transfer task) and the executive tests.

Results

Logarithmic transformations were performed on tracing time and errors on the computerized mouse tracing task in order to increase homogeneity of variance. Among the total sample, 3 10-year-old children and 1 adult were removed from all analyses because their total number of errors and/or their tracing time in the procedural task was more than 2.5 standard deviations from the mean for their group. All effects were assessed for significance at the $p = .05$ level. For planned comparisons, a Bonferroni correction was used to correct for the use of multiple tests (Type I error).

Initial performance with the mouse in its usual orientation

Age group differences in the ability to handle the mouse were revealed through an analysis of variance (ANOVA) on tracing time in the initial tracing task. There was a significant main effect of age group on tracing time, $F(2,69) = 17.12$, $p < .001$, $\eta_p^2 = .33$. Planned comparisons indicated that

7-year-olds' performance ($M = 29.96$) was significantly slower than that of 10-year-olds and adults ($Ms = 20.43$ and 14.50, respectively); a marginal difference in speed between 10-year-olds and adults was found ($p = .06$).

Did familiarity with the use of the mouse in its usual orientation have an impact on performance with the inverted mouse?

Correlations performed within each age group between initial performance (with the mouse in its usual orientation) and the first inverted mouse task (pretest) were not significant (all $ps > .05$), indicating that initial familiarity with the use of a computer mouse had no impact on the use of the inverted mouse during the inverted mouse task.

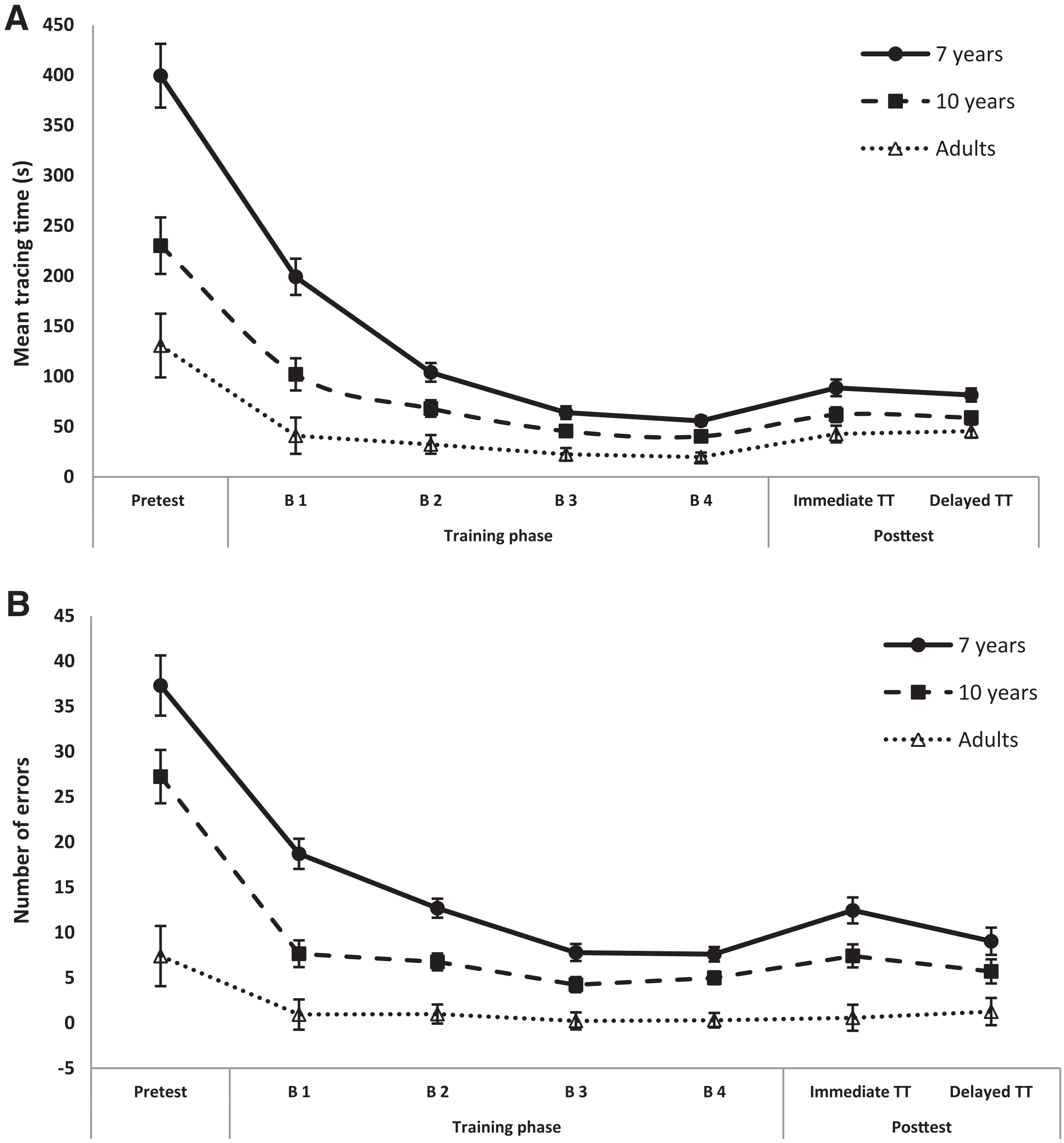

Fig. 1. Learning patterns of 7-year-old children, 10-year-old children, and adults. Data points indicate tracing time (A) and number of errors (B) by age group in the inverted mouse tracing learning tasks for each stage (triangle for training and star for pretest and posttest). TT, transfer task. Error bars represent standard errors.

Perceptuomotor procedural learning

To investigate whether there was any age-related improvement in procedural learning, we analyzed (a) performance and learning rate (i.e., the difference between Block 1 and Block 4) on the training task, (b) the transfer of the ability to a different figure, and (c) its retention after a 1-week delay.

Training task (triangle), Blocks 1 to 4

Participants' tracing time and errors for each block are illustrated in Figs. 1A and 1B. Although logarithmic transformations were computed on the data, the figure shows untransformed data per block to facilitate comprehension. To assess the performance and learning rate during the training task, ANOVAs with age group as a between-participants variable (3 groups) and block as a repeated measure (4 blocks) were performed (a) on speed of performance (mean tracing time by block) and (b) on error rate (mean number of errors by block).

Speed of performance. Results showed a significant main effect of block, $F(3,207) = 107.45$, $p < .001$, $\eta_p^2 = .61$, a significant age group effect, $F(2,69) = 33.82$, $p < .001$, $\eta_p^2 = .50$, and a significant Age Group × Block interaction, $F(6,207) = 4.15$, $p < .001$, $\eta_p^2 = .11$. This interaction showed that although all groups improved their completion time between Block 1 and Block 4, the improvement was not equivalent in the three age groups. Planned comparisons showed that although 7-year-olds performed more slowly than 10-year-olds on the first three learning blocks, the difference was no longer significant on the last block. The 7-year-olds showed a more pronounced improvement in speed between the first and last blocks than the 10-year-olds; however, this result was due to the 7-year-olds' particularly slow performance on the first block. In contrast, although the adults performed the task significantly faster than the 10-year-olds within each block, the decrease in tracing times between Block 4 and Block 1 was similar in the two age groups.

We also wanted to determine whether age group differences with the inverted mouse would remain after controlling for the ability to use the mouse in its usual orientation. To do so, an analysis of covariance (ANCOVA) was conducted with age group as an independent variable, tracing time on Block 1 as a dependent variable, and speed of performance with the mouse in its usual orientation as a covariate. Differences among age groups on the training task remained significant after controlling for the initial speed measure with the normally oriented mouse, $F(2,68) = 16.50$, $p = .001$.

Error rate. The same analyses were carried out on numbers of errors and generated results close to those obtained for the time measure; there were significant main effects of age group, $F(2,69) = 61.25$, $p < .001$, $\eta_p^2 = .64$, and block, $F(3,207) = 29.48$, $p < .001$, $\eta_p^2 = .30$, as well as a significant Age Group × Block interaction, $F(6,207) = 6.79$, $p < .001$, $\eta_p^2 = .16$. Planned comparisons showed that 7-year-olds made significantly more errors than 10-year-olds on the first three learning blocks and that 10-year-olds made more errors than adults on each block. Furthermore, intragroup comparisons showed differences across blocks: although the number of errors decreased between the first and last blocks for 7-year-olds and, more marginally, for 10-year-olds ($p = .06$), this was not the case for adults. The latter result can be explained by a floor effect because adults committed very few errors during the task ($M = 1.85 \pm 2.20$).

Transfer task (star)

Transfer to a different figure was tested by comparing performance (speed and error rate) between the pretest (before the training task) and the posttest (immediately after the training task, i.e., immediate transfer task). Results are illustrated in Figs. 1A and 1B.

Speed of performance. A 3 (Age Group) × 2 (Test) ANOVA with repeated measures on the second factor showed main effects of age group, $F(2,69) = 19.01$, $p < .001$, $\eta_p^2 = .35$, and test, $F(1,69) = 325.50$, $p < .001$, $\eta_p^2 = .82$, and a significant Age Group × Test interaction, $F(2,69) = 7.68$, $p < .001$, $\eta_p^2 = .18$. Performance on the immediate transfer task was faster than that on the pretest in all groups. As for the training task, 7-year-olds improved more between the two tests than 10-year-olds, but improvement in 10-year-olds and adults was similar.

Error rate. The same analyses on the number of errors showed significant main effects of test, $F(1,69) = 91.38$, $p < .001$, $\eta_p^2 = .57$, and age group, $F(2,69) = 52.97$, $p < .001$, $\eta_p^2 = .60$. No interaction was revealed, indicating that the error reduction between the pretest and the posttest (i.e., immediate transfer task) was similar in all age groups.

In addition, we checked whether this generalization effect would also be observed in a comparison of tracing time and error rate between the last trial of the training task (with triangle) and the immediate transfer task (with star). As before, the effects of test, $F(1,69) = 102.66$, $p < .001$, $\eta_p^2 = .60$, and $F(1,69) = 8.63$, $p = .004$, $\eta_p^2 = .11$, respectively, and age group, $F(2,69) = 18.37$, $p < .001$, $\eta_p^2 = .35$, and $F(2,69) = 44.25$, $p < .001$, $\eta_p^2 = .56$, respectively, were significant. Interestingly, the absence of a significant interaction suggests that transfer was similar in all age groups, $F(2,69) = 2.54$, $p = .09$, $\eta_p^2 = .06$, and $F(2,69) = 1.26$, $p = .29$, $\eta_p^2 = .03$, respectively.

Delayed transfer task (star)

Retention of the perceptuomotor skill over a 1-week delay was examined by comparing the time taken by each age group to trace the pattern on the immediate transfer task and after a 1-week delay (i.e., delayed transfer task). The effect of age group was significant (completion time: $F(2,69) = 12.07$, $p < .001$, $\eta_p^2 = .26$; errors: $F(2,69) = 26.02$, $p < .001$, $\eta_p^2 = .43$), but there was no significant effect of block (completion time: $F(1,69) = 0.05$, $p = .81$, $\eta_p^2 < .001$; errors: $F(1,69) = 3.51$, $p = .06$, $\eta_p^2 = .04$) and no significant interaction (completion time: $F(2,69) = 0.52$, $p = .59$, $\eta_p^2 = .01$; errors: $F(2,69) = 2.71$, $p = .07$, $\eta_p^2 = .07$). This analysis showed that the delayed transfer task was executed as well as the immediate transfer task in all age groups.

Correlation analyses

To study the link between executive functions and procedural learning during the first and last steps of the training process in each age group, Pearson's correlation analyses were conducted between measures of the three executive functions (inhibition, flexibility, and working memory) and Blocks 1 and 4 of the training task. Because completion time and number of errors on the training task were highly correlated (Block 1: $r = .76$, $p < .001$; Block 4: $r = .73$, $p < .001$), the two dependent measures were standardized within each block and combined into a composite *z*-score (see Kennedy & Raz, 2005). Thus, we had two indexes (*z*-Block 1 and *z*-Block 4) that were submitted to correlation analyses. Partial correlations were carried out to control for a motor speed effect using performance time on the control task with the mouse (i.e., in its usual orientation). All correlations are shown in Table 1.

Block 1

In 7-year-olds, no correlation was significant. In 10-year-olds, there was a significant correlation between Block 1 of the training phase and inhibition *z*-score (time) ($r = .71$, $p < .001$). No significant correlation was found with working memory or flexibility. In the adult group, the correlation between Block 1 and *z*-score for inhibition (time) was also significant ($r = .54$, $p = .01$); as in 10-year-olds, no significant correlation with working memory and flexibility was found.

Table 1
Correlations between executive functions and procedural performance (first and last training blocks) by age group.

Measure	7-year-old children			10-year-old children			Adults		
	Inhibition	Flexibility	WM	Inhibition	Flexibility	WM	Inhibition	Flexibility	WM
z-Block 1	–.04	–.00	–.08	.71***	.22	–.25	.54*	.37	–.31
z-Block 4	–.09	.09	–.23	.25	.28	–.01	.30	.04	–.28

Note. WM, working memory.
* $p < .05$.
*** $p < .001$.

Block 4

As predicted, no significant correlation was found between executive processes and performance on the fourth block of the training phase in any group.

Discussion

The main objectives of this study were (a) to determine whether procedural learning performance improves with age by comparing groups of 7-year-old children, 10-year-old children, and adults and (b) to investigate the role played by executive functions during the first and last stages of the acquisition of the skill in these three age groups. To do so, we created a computerized adaptation of the mirror tracing paradigm in which participants needed to trace a geometric shape with an inverted computer mouse.

Overall, our results showed a decrease in both tracing time and number of errors with practice in all age groups; all participants learned the skill regardless of their age. Importantly, the ability of children to transfer the skill to a different figure was similar to that of adults. Thus, participants not only learned the specific movements that needed to be performed in the training task but also were able to apply the new skill to a situation different from the one in which it was trained. Furthermore, performance on the transfer figure remained stable after a 1-week delay in all age groups.

More specifically, performance on the training task offers us information on how participants acquired the inverted mouse task. Although the adults performed the task significantly faster than the 10-year-olds within each training block, improvement in the two age groups was similar. On the contrary, the performance of 7- and 10-year-olds differed, revealing an effect of age in this range. Indeed, the youngest children showed the predicted pattern; they had much more difficulty in adapting to the task at the beginning of the learning process (they were slower and committed more errors on the three first learning blocks) than 10-year-olds. Importantly, 7-year-olds' performance attained the same level as that of 10-year-olds at the end of the learning process (on the fourth block of the training task). Therefore, our results showed two different things: first, that 7-year-olds had more difficulties with adaptation on the first training blocks and, second, that their learning curve confirms their ability to learn this new procedural skill as well as 10-year-olds do (the youngest children even learned at a higher rate). Ferrel-Chapus and colleagues (2002), using a quite similar task administered to 5- and 7-year-olds as well as to older children and adults, had already shown adaptation difficulties during the first learning step in the youngest children, followed by a significant improvement that was particularly pronounced in 5- and 7-year-olds. A similar pattern of results was also shown with a mirror tracing task in children with spina bifida compared with controls (Edelstein et al., 2004) and in studies comparing elderly and young participants (Beaunieux, Hubert, Pitel, Desgranges, & Eustache, 2009; Brosseau et al., 2007). The youngest children's greater improvement during the training task need not be interpreted as a reflection of greater learning capacity; rather, their learning curve was steeper due to poor initial performance (which leads to greater potential improvement). To further examine whether procedural learning performance differs with age, we also investigated the transfer of the learned ability to a shape different from the one used during training. The results confirm that although their initial performance levels were different, children and adults had a similar ability to apply the new skill to a different situation (as attested by a comparison of the last trial of the training task with the immediate transfer task).

Although age-related developmental differences are observed at the beginning of learning, it is difficult to determine precisely what mechanisms underlie them. As a first step, we verified that the initial difficulties of the youngest children were not due to a weaker ability to use the computer mouse. Our results showed that performance at the beginning of the inverted mouse task was not correlated with performance on the initial measure with the mouse used in its usual orientation in any of the three age groups. In addition, a covariance analysis controlling for performance speed with the normally oriented mouse confirmed the age group effect on performance on the first block of the training phase, showing that this speed measure did not explain the difference between age groups on the first block. Age-related differences in procedural learning appear to be more related to the nature of the task and, more specifically, to the type (and importance) of executive control required by the task. Indeed, the cognitive processes involved in the perceptuomotor adaptation tasks could be different from those usually demanded in other procedural tasks (Rouleau, Salmon, & Vrbancic, 2002). In this task, participants need to inhibit an overlearned association between visual perception and the hand movements used while tracing, contrary to other tasks such as the pursuit rotor task. Similar adaptation difficulties during the initial phases of perceptuomotor adaptation tasks have been reported in patients with prefrontal lesions (Schmidtke et al., 2002) as well as in elderly people, probably due to a decline in executive functions (Brosseau et al., 2007). In children, a great improvement in executive processes has been found between 6 and 9 years of age (e.g., Tillman, Thorell, Brocki, & Bohlin, 2008). In view of this, the initial differences observed in our study between 7- and 10-year-olds could be related to the time course of the development of executive functions during childhood.

In this context, the second objective of this study was to investigate the role played by three executive functions (working memory, inhibition, and flexibility) in three age groups during the first and last phases of the procedural learning process, which was done using correlation analyses. To our knowledge, this study is the first to investigate the role of these functions in procedural learning in children. Although results must be interpreted with caution given the small number of participants, they show, as expected, that inhibition abilities play a significant role in the performance of 10-year-olds and adults at the beginning of the training task (Block 1); no significant correlation was observed with flexibility or working memory. They also show that the involvement of inhibitory control dwindles with training; correlations were no longer significant at the end of the training task (Block 4). These results confirm that the ability becomes progressively less controlled and more automatic, which is consistent with a top-down conception of learning (Anderson, 2000; Beaunieux et al., 2006; Doyon & Benali, 2005) and, more specifically, with the current literature on perceptuomotor adaptation tasks, which suggests that inhibitory control would be particularly important in the first step of learning (e.g., Brosseau et al., 2007). On the other hand, correlation analyses showed no relation between 7-year-olds' executive functions and their performance at the beginning of the training phase. Overall, these findings suggest that the task used in this study elicits explicit processing (e.g., inhibition) at the beginning of learning; thus, adults and 10-year-olds likely outperformed the youngest children because of their superior inhibition processing abilities. Indeed, several studies have shown that inhibition is mature at around 10 years of age (e.g., Welsh et al., 1991). On this view, the youngest children had more difficulty in performing the task during the early learning stage because their inhibition abilities could not be sufficiently developed to help them perform the task. Thus, they may rapidly switch from explicit strategies to more implicit learning processes, permitting them to perform as well as 10-year-olds by the end of training (because implicit processes are less age dependent).

However, the developmental literature on procedural learning (e.g., Karmiloff-Smith, 1992) leads us to consider an alternative hypothesis, according to which procedural skill learning need not involve explicit declarative knowledge and the knowledge acquired can be stored in an implicit form as soon as learning begins. In this view, the 7-year-olds in our study may have started the procedural task in a less controlled fashion than the older children and adults because their explicit mechanisms (including inhibition) are less developed than those of older children; this would at least partially explain not only the absence of correlation between inhibition measures and procedural performance in 7-year-olds but also why they made so many errors at the beginning of learning. In favor of this view, several studies in children using perceptuomotor adaptation tasks have yielded results suggesting that children and adults use different strategies to adapt their movements; for example, Ferrel-Chapus and colleagues (2002) showed that in mirror tracing situations, the youngest children (5- and 7-year-olds) have more difficulties in understanding the visual disturbance, whereas older children are aware of the rotation. Tahej, Ferrel-Chapus, Olivier, Ginhac, and Rolland (2012) confirmed this hypothesis, showing that, when confronted with large perceptuomotor rotations (>45°), 5-year-olds have difficulty in performing the mental rotations and, unlike adults, do not seem to use explicit strategies to reach the target.

In summary, the current study offers new information on the development of procedural learning in adaptation tasks involving the inhibition of an overlearned response in order to create a new visuomotor association. Like the results of some previous studies (e.g., Ferrel-Chapus et al., 2002), our findings indicate that, in this context, age has an effect on performance during the initial phases of learning but not on the learning rate (in fact, due to their poor initial performance, the learning rate of the youngest children was higher than that of the older groups). We suggest that this age effect could be at least partly related to the time course of the development of executive functions during childhood; specifically, in the inverted mouse task that we used in this study, inhibition abilities seem to have played an important role in the initial (i.e., first block) performance of 10-year-olds and adults but not of 7-year-olds (probably because these functions are not yet sufficiently developed in this age group). Moreover, inhibition clearly cannot in itself explain all of the observed group differences. The fact that the progressive emergence of other abilities, such as visual and proprioceptive integration (Ferrel-Chapus et al., 2002), is not complete in young children might also contribute to their difficulties with sensorimotor adaptation. Certainly, executive processes contribute to diminishing error production, to the planning of efficient behavior, and to the inhibition of inappropriate routines, helping to optimize performance early in the learning process; however, the still partial development of the youngest children's executive processes does not prevent them from learning a perceptuomotor skill as well as older children and adults. Therefore, one important result of this study is that although inhibition functions, so long as they are sufficiently developed, may play a key role during the first steps of learning a new skill that requires perceptuomotor adaptation, they would not be a necessary condition for learning to occur. Currently, it remains difficult, on the basis of either our results or the literature in general, to determine which processes, implicit or explicit, are involved during the early learning phase in young children. Further studies using, for instance, a dual-task paradigm are needed in order to fully understand the role of explicit mechanisms at the beginning of procedural learning at different stages of development. Studies on procedural learning in children are still too limited, and research in this area should also continue in the future in order to further our understanding of the nature and importance of the executive mechanisms involved in procedural learning by comparing different paradigms (including situations that do not require the inhibition of an overlearned association between vision and motor behavior).

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