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The effect of response-to-stimulus interval on children's implicit sequence learning

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ABSTRACT

The current study examined, for the first time in a developmental perspective, the effect of response-to-stimulus interval (RSI) in incidental sequence learning (SL). Children aged 4, 7, and 10 years performed a serial reaction time (SRT) task in which the RSI was systematically manipulated (0, 250, 500, or 750 ms). SL (difference in reaction times between fixed and random blocks) was not observed for the youngest children whatever the RSI condition, whereas the 7-year-olds learned the sequence only in the 250-ms RSI condition and the 10-year-olds exhibited SL in all temporal conditions except the 500-ms RSI condition. Finally, the results suggest that conscious awareness of the sequence emerges only in older children faced with the 500- and 750-ms RSI conditions. The discussion questions the robustness of implicit learning processes in the light of individual and contextual factors.

Introduction

The serial reaction time (SRT) task (Nissen & Bullemer, 1987), also referred to as the sequence learning (SL) task, is one of the most popular paradigms dedicated to investigating implicit learning abilities. In this task, participants need to track a visual target moving across four to six possible locations and respond as fast and accurately as possible by pressing the key associated with the target's location. Participants are not aware that the target's movements follow a fixed sequence that is

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repeated throughout blocks. The decrease in reaction time (RT) with practice indicates that participants become familiar with the task and sensitive to the fixed sequence of the target's movements. To distinguish between sequence-specific learning and learning of the basic visuomotor components of the task, random sequences are inserted during the training phase. Shorter RTs on fixed sequences compared with random sequences reflect sequence-specific learning. Some studies have reported a difference in RTs between repeated and random sequences as early as the sixth (Perruchet & Amorim, 1992) or seventh (Nissen & Bullemer, 1987) presentation of the fixed sequence. Because no direct instruction focuses on the presence of regular patterns in the target's movements, this task is considered as one of the most suitable methods for assessing implicit learning abilities. In addition, the visuomotor components of this task allow this paradigm to be used with relatively young children.

A growing number of studies have investigated SL in typically developing children. For instance, Meulemans et al. (1998) showed that incidental SL operated similarly in both 6- and 10-year-old children as well as in adults. Karatekin et al. (2007) also found globally age-independent implicit learning performances at 8 to 10, 11 to 13, and 14 to 17 years of age as well as in young adults (see also Mayor-Dubois et al., 2016, for age-independent learning in 8-, 10-, and 12-year-old children). Thomas and Nelson (2001) extended these investigations to younger children and observed SL in 4-, 7-, and 10-year-old children. Thus, these findings corroborated Reber's (1993) postulate that implicit learning is a robust phenomenon. However, contradictory data have been observed (e.g., Fischer et al., 2007; Savion-Lemieux et al., 2009; Thomas et al., 2004; Weiermann & Meier, 2012). For instance, Karatekin et al. (2007) reported individual differences. Although all the 10-year-olds showed SL, 13% of the 7-year-olds and 28% of the 4-year-olds showed motor learning but failed to exhibit sequence-specific learning (i.e., performance improvement during the five blocks but little or no performance disruption during the random block). The authors also observed that other learning measures, such as anticipatory responses, were age dependent. In the same vein, Thomas et al. (2004) reported that 7- to 11-year-olds required more trials to learn the sequence and exhibited a reduced magnitude of learning and different neural patterns of brain activation when compared with adults. Studies have also reported that variations of the SL task affect performance differently with age. For instance, De Guise and Lassonde (2001) observed that 6- to 8-, 9- to 11-, 12- to 14-, and 15- and 16-year-old participants learned the sequence under unimanual conditions, whereas the two younger groups failed to learn the sequence in the bimanual condition. Hodel et al. (2014) compared learning on fixed-paced adaptations (interstimulus interval [ISI]) and on self-paced adaptations (response-to-stimulus interval [RSI]) of an SL paradigm in 4-year-old children (ISI = 1500 ms, RSI = 500 ms) and in adults (ISI = 750 ms, RSI = 500 ms). Although the children performed better in the self-paced condition than in the fixed-paced condition, they showed reduced learning performance compared with the adults whatever the stimulus presentation condition. The authors concluded that developmental differences in implicit SL reflect developmental changes in broader constructs elicited by specific task demands such as attention.

Recently, a systematic review aimed to investigate sequence learning in a life-span perspective. The meta-analysis conducted by Zwart et al. (2019) contrasted three models of different developmental trajectories of SL. The first model suggested that SL is age independent, whereas the other two models predicted age-related changes in SL. Although these two age-dependent models postulated a decline with age, one predicted an increase during childhood that reaches its peak during young adulthood, whereas the other predicted a plateau during childhood followed by a decline. The authors reported that 17 of the 50 studies included in the meta-analysis supported an age-invariance model. These included the previously cited studies of Meulemans et al. (1998), Thomas and Nelson (2001), and Mayor-Dubois et al. (2016). Zwart et al. (2019) pointed out that similar conclusions could be drawn from implicit learning studies carried out with different paradigms, for example, implementing a graphomotor task (Vinter & Perruchet, 2000) or an artificial grammar (López-Ramón, 2007). However, the authors concluded that most of the studies reviewed in their meta-analysis (33 of 50) supported models predicting age-dependent learning. For instance, Lukacs and Kemeny (2015) reported results from three different paradigms, all arguing for a model in which SL improves with age, with a peak between 18 and 35 years, a slight decline up to 65 years, and a larger decline again after 65 years. In their turn, Janacsek et al. (2012) found that the age groups from 4 to 12 years showed the strongest learning effect, with a decline setting in early among the older groups (14–85 years). This observation supports a model with a plateau during childhood followed by a decline.

To conclude, although there is no consensus on the developmental trajectory of implicit learning, especially from early childhood to adulthood, age-dependent learning models account for most of the empirical evidence. Zwart et al. (2019) concluded that the inconsistent findings are partly due to methodological issues. They pointed out that the use of raw RTs to measure learning supports models predicting a peak during young adulthood, whereas the use of normalized RTs supports models involving a plateau during childhood followed by a decline. For this reason, further SL studies should carry out RT-based analyses on both raw and *z*-normalized RTs.

However, Zwart et al. (2019) limited their discussion of the heterogeneity in the characteristics of the studies to the dependent variables used to assess SL (raw vs. normalized RTs). Nevertheless, the disparity between the procedures used in previous studies suggests that there are many potential sources of variations that could account for the inconsistent findings. Even though these factors have not yet been systematically studied in a developmental perspective, they have aroused some interest in the implicit learning field. These factors include sequence complexity (e.g., Cleeremans & McClelland, 1991), the number of trials and blocks (e.g., Gaillard et al., 2009; Howard et al., 2004), the response mode (e.g., De Guise & Lassonde, 2001), the duration of the rest periods (e.g., Fanuel et al., 2020, 2022), and the RSI (e.g. Frensch & Miner, 1994). Considering this latter parameter (RSI), a rapid analysis of a large number of the studies cited by Zwart et al. (2019) revealed that the temporal organization of the sequence varied greatly across studies, which implemented different RSI conditions (0, 100, 250, 300, 500, or 700 ms) and different fixed presentations of the stimuli (500, 600, 800, or 1000 ms), themselves interspersed by different ISIs (0, 500, 1000, or 1200 ms). RSI particularly attracted our attention because previous studies have shown that the use of a varied RSI, manipulated as an independent variable, could significantly affect adults' SL. Before arguing for the need to extend this research within a developmental perspective, we briefly review much of the literature devoted to adults and introduce certain theoretical assumptions about the associative learning mechanisms involved in SL that have motivated the manipulation of RSI in SL studies.

Frensch and Miner (1994) manipulated RSI in an adult population in order to empirically test a theoretical framework (adapted from Cowan's (1988) view) for understanding implicit learning. The authors assumed that associative learning mechanisms involved in sequence learning rely on short-term memory capacity and the level of activation of the to-be-learned information. They manipulated the rate of presentation of the stimuli (via RSI) to test predictions drawn from this theoretical framework. The first prediction was that learning should be more likely to occur when the stimuli are presented closer together in time because stimuli are more likely to be simultaneously active in short-term memory in this situation than when they are presented with a greater temporal interval. Second, learning should be more likely to correlate with short-term memory span measures when the temporal interval between the stimuli is longer rather than shorter, because the former condition is more likely to cause the limit of short-term memory capacity to be reached. In their first experiment, they set RSI to either 500 or 1500 ms in order to operationalize the activation level and observed that an RSI of 1500 ms (i.e., lower activation level) led to lower SL levels than an RSI of 500 ms. However, short-term memory span was correlated with learning only under intentional instructions and with an RSI equal to 500 ms. The authors suggested that the participants in this learning condition may have learned larger parts of the sequence. As a result, the short-term memory limits of the participants with lower capacities would have been reached, thereby revealing a correlation between learning and short-term memory. At the same time, a floor effect may have occurred in the remaining conditions. Additional results also revealed that this correlation is more likely to arise when the available capacity is artificially reduced in a dual-task condition (Experiment 2) and that learning in old adults, who are known to possess lower short-term memory capacities, is more affected under dual-task conditions than is the case in young adults (Experiment 3). Taken together, these findings argue that short-term memory and the level of activation of the to-be-learned elements play a role in SL. (For more recent studies investigating the role of working memory in young and old adults' SL, see, e.g., Bo et al., 2011, 2012.)

Other studies also emphasized that SL is affected by inconsistent RSI (half the trials had a 500-ms RSI and half had a 2000-ms RSI) (Stadler, 1995). However, Willingham et al. (1997) showed that short inconsistent RSIs (50, 450, and 850 ms) did not negatively affect SL and that participants who switched from long RSIs (1500 or 2000 ms) to short RSIs showed evidence of learning, but not participants who switched from short to long RSIs. They concluded that manipulating RSI influenced the indirect RT-based measure of SL but not SL per se. The same year, Perruchet et al. (1997) found that the absence of RSI prevents SL (Experiment 2), unlike the standard 250- or 500-ms RSI conditions, but that manipulating RSI did not influence the formation of explicit knowledge of the sequence. Frensch et al. (1994) also showed that manipulating RSI (500–1500 ms) affected SL but had only a minor effect on measures of explicit knowledge. They suggested that the higher, albeit not significantly so, explicit performance with an RSI of 500 ms than with an RSI of 1500 ms might argue in favor of the RSI effect observed on indirect measures of learning. To this end, they reanalyzed their results after excluding participants with explicit performances above 50%. However, this did not affect the pattern of results. Contrary to Frensch and Miner (1994), Perruchet et al. (1997) predicted that RSI should affect indirect RT-based measures of learning and, in particular, that suppressing RSI would prevent the action of sensorimotor anticipation processes that support the improvement in RT without, however, affecting the measures of explicit knowledge. Taken together, these findings may argue for a dissociation between implicit and explicit knowledge.

This conclusion was challenged by Destrebecqz and Cleeremans' (2001, 2003) studies in which inclusion and exclusion generation tasks inspired by Jacoby's (1991) process dissociation procedure (PDP) and a fragment recognition task were used in addition to the SRT task. The participants exposed to the 250- and 1500-ms RSI conditions succeeded in the exclusion and fragment recognition tasks, whereas those trained with no RSI did not, thereby suggesting that the no-RSI condition resulted in unconscious knowledge of the sequence, whereas longer RSIs allowed the development of conscious awareness of the sequence. Their results indicated that increasing RSI only improved explicit knowledge acquisition and suggested a functional dissociation between implicit and explicit learning. The authors argued that the time available to process the stimuli affects the quality of the representation of the sequential constraints and thus the knowledge of the sequence. When participants were trained with RSI (250 ms and more), it gave them more opportunity to develop high-quality memory traces of the stimuli and to link them together to shape explicit sequential knowledge. However, in the absence of RSI, participants acquired implicit knowledge of the sequence able to influence indirect measures of leaning. However, explicit knowledge was not detected because the weakness of the memory traces developed in this time-constrained condition did not make it possible to control the responses in the generation and recognition tasks used as explicit tests (Destrebecqz & Cleeremans, 2001). However, conflicting results have shown that participants were able to discriminate between novel and familiar fragments of the sequence or to inhibit knowledge of the sequence in the 0- and 250-ms RSI conditions in the exclusion task (Norman et al., 2006; Shanks et al., 2003, 2005; Wilkinson & Shanks, 2004) and that increasing RSI from 0 to 500 ms did not improve sequence recognition (at least for participants receiving incidental instructions; Rünger, 2012).

In sum, previous findings show that there is no consensus on precisely how RSI affects implicit and/or explicit knowledge of the sequence. However, they suggest that suppressing or lengthening RSI affects SL (relative to RSIs of 250 and 500 ms). The theoretical frameworks to which previous studies refer suggest that lengthening RSI causes the limits of the short-term memory span to be reached and reduces the number of simultaneously activated to-be-learned elements (Frensch and Miner, 1994). By contrast, suppressing RSI prevents anticipatory sensorimotor processes from operating (Perruchet et al., 1997) or does not give participants the opportunity to develop stronger high-quality representations of the sequential constraints and prevents them from developing conscious knowledge of the sequence (Destrebecqz & Cleeremans, 2001, 2003) because the time available to process each serially presented stimulus is reduced (e.g., Cleeremans & Jiménez, 2001). This last account suggests that processing speed capacities also play a significant role in time-constrained SL situations (for another account of the role of processing speed in SL, see, e.g., Kaufman et al., 2010; Salthouse et al., 1999).

Interestingly, Frensch and Miner (1994) concluded their presentation by adopting a developmental perspective (comparing young and older adults). In their third experiment, they investigated whether age-related differences in short-term memory capacity affect the degree of implicit learning. The authors chose to drop the RSI manipulation, with an RSI of 200 ms in all cases, but to manipulate task load (single vs. dual task) in order to artificially reduce available short-term memory capacity. They assumed that age-related differences in learning should be observed under a dual-task condition because older adults are known to have a lower short-term memory capacity than young adults (e.g., Salthouse, 1991). Consequently, they interpreted the larger age differences in the dual-task condition as being consistent with the important role of short-term memory in SL. Following the same reasoning, because cognitive functioning, including executive functions, processing speed, attentional resources, and short-term/working memory span, develops with age (e.g., Diamond, 2013; Gathercole, 1999; Hitch & Halliday, 1983; Kail, 1991), we assumed that age-related differences between young and older children should be more likely to emerge in situations where the capacity limits of younger children are reached. This applies to processing speed capacity when the RSI is suppressed and to short-term/working memory capacity and level of activation of the to-be-learned stimuli when the RSI is lengthened.

To our knowledge, the effect of RSI in SL has never been investigated in children. To this end, 4-, 7-, and 10-year-old children participated in an SRT task where the RSI was systemically manipulated (0, 250, 500, or 750 ms). Based on the literature on adults, we expected that extreme values of RSI (0 and 750 ms) should affect SL. Because associative processes would operate on the contents of the attentional focus (see Perruchet & Vinter, 2002) or of the short-term memory span (Frensch & Miner, 1994), which is constrained in time and space, lengthening the temporal distance between the successive elements of the sequence would make these elements harder to associate. However, although the 0-ms RSI condition may appear to be the most favorable condition for establishing associations because the temporal distance between elements is reduced to a minimum (i.e., the participant's RT), we hypothesized that the processing of successive elements may overlap in this condition and disrupt the integration of the stimuli in a serial order. In addition, tolerance to a larger range of RSIs (shorter and longer than 250- and 500-ms RSI) should appear with age. Moreover, because manipulating RSI may also affect the conscious awareness of the sequence per se and not only RT performance, we introduced a subsequent generation task comprising an inclusion phase and an exclusion phase adapted from Jacoby's (1991) PDP. The purpose of this generation task was to assess conscious and unconscious influences resulting from the learning phase. In the light of findings in adults, reducing the RSI to 0 ms should eliminate any conscious awareness of the sequence, whereas increasing the RSI should promote conscious awareness of the sequence (Destrebecqz & Cleeremans, 2001, 2003).

Method

Participants

A total of 291 2nd-year kindergarten pupils, 2nd graders, and 4th graders (133 girls and 158 boys), aged 4 years (*n* = 98), 7 years (*n* = 97), and 10 years (*n* = 96), participated in the experiment. Within each age group, the children were randomly assigned to one of four RSI conditions (0, 250, 500, or 750 ms). Table 1 presents the characteristics of the groups.

According to the teachers, none of the children enrolled in the current experiment exhibited any atypical development (i.e., none of them had reached developmental milestones earlier or later than typically developing children of the same age groups on the basis of the information available to the teachers: school performance, no attendance in educational care services, no school-based adaptations for children with special needs, etc.). The children's vision was normal or corrected to normal, and more than 90% of them were right-handed. This study was conducted in accordance with the ethical standards set out in the 1964 Declaration of Helsinki, and written parental consent was obtained for each child.

Material

A computer game involving mole characters appearing sequentially in four possible locations was employed in order to instantiate an SRT task adapted for young participants (see Fig. 1). In this game,

Table 1
Characteristics of the groups.

Age	Mean age (years;months)	*n*	RSI (ms)	*n*	Mean age (years;months)	Sex (F/M)
4 years	4;8 (range = 3;10–5;2)	98	0	30	4,8	12/18
			250	22	4,7	10/12
			500	21	4,7	10/11
			750	25	4,5	13/12
7 years	7;4 (range = 6;2–8)	97	0	27	7,4	12/15
			250	23	7,5	11/12
			500	21	7,5	10/11
			750	26	7,1	12/14
10 years	10;6 (range = 9;2–11;7)	96	0	26	10,8	10/16
			250	23	10,7	11/12
			500	24	10,7	11/13
			750	23	10,2	11/12

Note. RSI, response-to-stimulus interval; F, female; M, male.

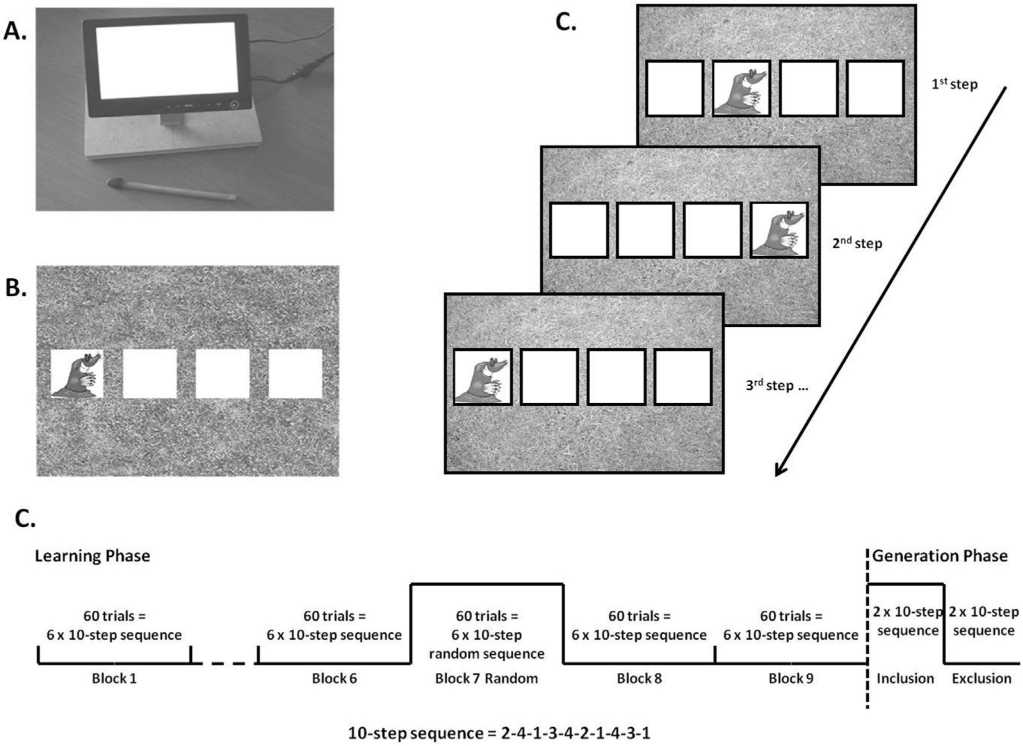

Fig. 1. Experimental apparatus composed of a touchscreen and a hammer (A) used to interact with the video game (B) displaying the fixed and random sequences across the blocks (C) and allowing the generation of sequences during the (inclusion/exclusion) generation task.

inspired by the Whack-A-Mole arcade game (created by Aaron Fechter in 1976), the children were asked to “chase and catch as many moles as possible as soon as they appear on the screen and as fast as possible.” To chase moles, the children used an 18-cm hammer to “squash” target moles on an 8-inch (1920 × 1080 pixels) touchscreen (Fig. 1A) connected to a computer that recorded the children’s

RTs between the appearance of the stimulus and the subsequent impact as well as the stimulus position and response correctness. The hammer consisted of a wooden handle finished with a rubber tip. This tool was selected to favor proximal control rather than distal control (such as pressing keys) in order to limit the influence of age-related motor skills, which is greater in the case of distal motricity (Exner, 2001; Gesell & Amatruda, 1947). The touchscreen displayed a green background depicting the grass of a garden with four horizontally aligned white windows (384 × 384 pixels and 77 pixels per intervening space) corresponding to the four locations where the moles appeared, which were coded 1, 2, 3, and 4 from left to right (Fig. 1B). For the purposes of the experiment, the computer program made it possible to adjust the RSI in the setup menu. The RSIs (0, 250, 500, and 750 ms) were selected on the basis of an extensive, but not exhaustive, review of the literature. This review revealed that robust sequence-specific learning (i.e., learning that is independent of the age of the participants) typically emerges when the RSI is set to 250 ms (e.g., Meulemans et al., 1998) or to 500 ms (e.g., Howard & Howard, 1992; Nissen & Bullemer, 1987; Thomas & Nelson, 2001). In addition, these RSIs give the participants enough time to process the stimuli and develop high-quality representations and explicit sequential knowledge (Destrebecqz & Cleeremans, 2001, 2003). Thus, RSIs of 250 and 500 ms were selected for the core conditions of the current experiment and were compared with shorter and longer RSIs. We also decided to introduce a no-RSI condition (RSI set to 0 ms) because the absence of RSI is known to negatively affect either the indirect measure of SL (Perruchet et al., 1997), namely sequence-specific learning, or the direct measure of learning by reducing explicit knowledge of the sequence (Destrebecqz & Cleeremans, 2001, 2003). Finally, the RSI in the longer RSI condition was set to 750 ms even though we had initially planned to set it to 1500 ms based on previous findings revealing lower levels of SL with an RSI of 1500 ms than with an RSI of 500 ms (Frensch & Miner, 1994). However, two important observations prevented the use of a longer RSI of 1000 ms or more in very young children. First, preliminary investigations revealed that the RTs and error rates dramatically increased in younger children, suggesting that they were insufficiently motivated to engage in these slow rate presentation conditions, thereby affecting the attentional processing of the sequences to be learned. When RSI was set to 750 ms, the accuracy rate remained comparable to that in faster presentation rate conditions. Second, Frensch and Miner's (1994) theoretical framework states that the level of activation of the to-be-learned stimuli depends on the temporal distance between successive stimuli. This suggests that what matters is the length of the ISI. Although it is recommended to manipulate RSI rather than ISI in children (Hodel et al., 2014), a desired average ISI can be approximated on the basis of the average RTs by adding an adapted RSI. To our knowledge, because adults generally exhibit SRT in a range of RTs between 250 and 300 ms, adding an RSI of 1500 ms would result in an average ISI of between 1750 and 1800 ms. Following the same reasoning, adding an RSI of 750 ms to an average RT of 1000 ms in 4-year-olds (for an estimate of average RTs in 4-year-olds, see Thomas & Nelson, 2001) would result in an average ISI of 1750 ms, which is equivalent to that resulting from the RSI of 1500 ms used for adults in Frensch and Miner (1994). Finally, setting the longer RSI to 750 ms also made it possible to track a gradual improvement in the quality of representations, which we expected to lead to a gradual improvement in the conscious awareness of the sequence (Destrebecqz & Cleeremans, 2001, 2003), as was successfully observed in previous studies. (For the adoption—for comparative purposes—of gradual RSI in this range [0, 250, 500, 750, and 1000 ms], see, e.g., Hui et al., 2018, and Zhang & Liu, 2021.)

Moles appeared successively in different windows in a predefined order within fixed blocks (Fig. 1C). A fixed block comprised a fixed sequence consisting of 10 locations repeated six times (60 trials). The fixed sequence (2-4-1-3-4-2-1-4-3-1) was the same as that used in Meulemans et al.'s (1998) study. Random sequences were built for the familiarization phase and to produce the random blocks. The random sequences comprised 10 locations, with the four possible locations occurring in the same proportions as in the fixed sequence (i.e., Locations 1 and 4: 30%; Locations 2 and 3: 20%) but ordered randomly, except that immediate repetitions and back-and-forth movements were excluded, in the same way as in the fixed sequence. The random block comprised six different random sequences (60 trials), and 20 different random blocks were built in order to provide most of the participants with a different random block within each age group and experimental condition.

Procedure

Familiarization phase

The participant sat in front of the touchscreen and the experimenter set the RSI parameter according to the experimental condition to which the child was randomly assigned. The familiarization phase started with the following instructions: “You will see moles popping up out of their holes, and you will have to catch as many moles as possible as soon as they appear by squashing them with this little hammer. To catch as many moles as possible, you have to go as fast as you can and be as accurate as possible. You will train first before starting the game. Hit the moles as soon as they pop up out of their holes. Are you ready? Let’s go!” The background screen with the four windows appeared after a 2-s delay, with the first mole in one of the four locations. After the participant hit the mole at the correct location on the touchscreen, the mole disappeared and the next mole appeared in a different location according to a random sequence. This continued until a 10-location sequence was completed. A short break allowed the experimenter to ensure that the participant had correctly understood the task instructions; if not, feedback on the child’s behavior was provided by the experimenter and a second familiarization sequence of 10 random locations was proposed using the following instructions: “Have another try before starting the game. Are you ready? Let’s go!” The familiarization phase ended after the participant had completed the sequence as requested by the instructions.

Learning phase

The child was told, “Now that you know how to catch moles, the game will begin. Hit as quickly and accurately as possible as soon as you see a mole appear so that you can catch as many moles as possible. Are you ready? Let’s go!” The learning session comprised nine blocks of 60 trials (Fig. 1C). Blocks 1 to 6 (fixed blocks) each consisted of six presentations of the fixed sequence (total of 360 trials). Block 7 (random block) consisted of six different random sequences (60 trials). The fixed sequence was restored in Blocks 8 and 9 (fixed blocks; 120 trials) to ensure that any increase in RTs that might be observed in Block 7 was not due to fatigue. A 30-s break separated each block and allowed the experimenter to maintain the participant’s motivation. The learning phase ended when the participant had completed the nine blocks.

Generation test phase

The generation phase included an inclusion task followed by an exclusion task as in Jacoby’s (1991) PDP. This procedure needed to meet the challenge of making the inclusion/exclusion instructions clear for very young children. To satisfy this requirement, we drew inspiration from the study by Bremner et al. (2007), who successfully administered the PDP to 2-year-old children and showed that they were able to develop cognitive control of sequential knowledge following incidental learning of a deterministic sequence of spatial locations. The instructions of their dog-chasing-cat game were adapted to our Whack-A-Mole game. Systematic interviews asking the children to repeat and explain what they needed to do under the inclusion and exclusion instructions confirmed that these instructions were clearly understood by all the participants.

Inclusion task. The child was told that the moles had actually frequently taken the same repeating “route of hideouts” in some parts of the game. The child was told that he or she was going to play the role of a mole and was asked to remember the path the moles often took in some parts of the game and to exactly reproduce the route of hideouts that the moles took most frequently. The first two hideouts were shown to the child, who then needed to continue as the mole had previously done in accordance with the following instructions: “Now, it’s your turn to be a mole. When you hit a hideout with your hammer, it’s as if you were leaving your hiding place, like the mole just did before. Now try to remember the exact repeating route of hideouts the moles have taken frequently in some parts of the game just as you have already seen. Hit the hideouts to show me how the moles went from one hiding place to another. To help you, I will show you the first two hideouts where the moles appeared, you will hit the moles as fast as possible just like before, and then you will continue by hitting the next hiding places you remember the moles using lots of times before. Are you ready? So, hit the moles and show me the route they take next, the repeating route you have seen before in some parts of the game." The first two locations corresponded to the regular sequence the child had been presented with (2-4-). Therefore, the child needed to generate the exact route of hideouts that the moles often followed during the learning phase. The inclusion task finished once the child had generated a sequence of 20 locations. A black screen was displayed, and the experimenter introduced the exclusion task.

Exclusion task. During the exclusion phase, the experimenter asked the child to show a route of hideouts totally different from the one the moles had followed most frequently during the learning phase. The instructions were as follows: "Now you will play a different game. To help the moles escape from hunters who know the route of hideouts the moles often followed during the game, you will show the moles a route of hideouts totally different from the one they often followed during the game. To help you find a brand new route of hideouts, a route you have never seen before, I will show you how it can start. We will hit the hideouts as fast as possible, and then you will continue by hitting new hiding places to show the moles a route of hideouts totally different from the one they took frequently in some parts of the game. Are you ready?" The first two locations corresponded to a succession of locations that never occurred in the regular sequence (2–1-). The child needed to hit the moles and then continue by hitting the windows in order to make moles appear and generate a totally different route of hideouts from the one the moles had often followed during the learning phase. The exclusion task finished once the child had generated a sequence of 20 locations. A short animation with a mole congratulated the child and announced the end of the game.

Coding and analysis of the data

Mean RTs were calculated for each block after incorrect responses (i.e., errors of location) and responses that were faster than 100 ms or more than 3 standard deviations slower or faster than the mean had been excluded. In addition, participants who produced more than 50% of excluded responses were also excluded from the analysis (4 participants: 3 4-year-olds in the 500-ms RSI condition and 1 7-year-old in the 250-ms RSI condition). This resulted in the elimination of 6.7% of the data for the remaining participants. Analyses were performed on the *z*-normalized RTs in order to control baseline differences between age groups and experimental conditions. For example, Hodel et al. (2014) used *z*-normalized RTs because preliminary analyses showed that adults responded more quickly than children. According to the authors, this justified the adoption of this approach. Like Hodel et al., we normalized RT scores in line with Thomas et al.'s (2004) data transformation procedure, which is based on each individual's mean and standard deviation. However, because there is little consensus about whether analyses should be run on raw or *z*-normalized RTs, and due to the different conclusions drawn from analyses based on the different procedures (e.g., Janacsek et al., 2012; Lukacs & Kemeny, 2015; Zwart et al., 2019), we also performed and summarized the same analysis on the raw data. The sequence-specific learning effect was first assessed based on accuracy as a function of age and RSI. To this end, a 2 (Sequence: average fixed blocks [6–8] or random block [7]) × 4 (RSI: 0, 250, 500, or 750 ms) × 3 (Age: 4, 7, or 10 years) mixed analysis of variance (ANOVA) was performed on the mean proportion of correct responses. Sequence-specific learning was then assessed by comparing mean RTs in the fixed blocks that preceded (Block 6) and followed (Block 8) the random block with that recorded in the random block (Block 7). A 2 (Sequence: fixed or random) × 4 (RSI: 0, 250, 500, or 750 ms) × 3 (Age: 4, 7, or 10 years) mixed ANOVA was performed and follow-up analyses were carried out using *t* tests to compare fixed blocks (6–8) and the random block (7) for each age and RSI condition. A Bonferroni correction was applied in order to adjust the alpha threshold (*p* value) because of the increased risk of Type I errors when performing multiple tests. In addition, explicit knowledge of the sequence per se was determined by computing the proportion of successions of two or three locations corresponding to the fixed sequence in both the inclusion and exclusion tasks. This makes it possible to evaluate whether the children were able to control their knowledge of the sequence, that is, to reproduce the fixed sequence under inclusion instructions and to exclude it under exclusion instructions. One-sample Student's *t* tests were run to compare the children's generation of correct chunks under inclusion and exclusion instructions with chance. The baseline probability of producing legal successions of two locations took account of the fact that the sequence allowed 10 legal successions among 16 possibilities. However, to make the computation of the baseline probability more conservative, we did not consider the four possible repetitions, which were probably too easy to discover (and consequently to avoid, e.g., under inclusion instructions), in the computation [10 / (16–4) = 83.33%]. The same computation made it possible to set the baseline probability of producing a succession of three elements corresponding to the sequence at 27.78%.

Results

Accuracy

A 2 (Sequence: fixed = average of Blocks 6–8 or random = random Block 7) × 4 (RSI: 0, 250, 500, or 750 ms) × 3 (Age: 4, 7, or 10 years) mixed ANOVA was performed on the mean proportion of correct responses (Fig. 2). Results revealed no main effect of sequence, $F(1, 275) = 0.30$, $p = .58$, $\eta_p^2 = .001$, but revealed main effects of age and RSI, $F(2, 275) = 43.85$, $p < .0001$, $\eta_p^2 = .24$ and $F(3, 275) = 5.14$, $p = .0018$, $\eta_p^2 = .053$, respectively, with accuracy increasing with age ($M_{4\text{years}} = .87$, $M_{7\text{years}} = .94$, $M_{10\text{years}} = .97$) and with longer RSI ($M_{0\text{ms}} = .87$, $M_{250\text{ms}} = .94$, $M_{500\text{ms}} = .97$, $M_{750\text{ms}} = .97$). Interestingly, age and RSI did not interact, $F(6, 275) = 0.69$, $p = .66$, $\eta_p^2 = .015$, and no other two-way or three-way interaction reached the level of significance (*F*s < 1). The analysis of accuracy (≥87%) revealed that the participants were able to complete the task irrespective of the age and RSI conditions.

Sequence-specific learning

The mean raw RTs and *z*-transformed RTs as a function of blocks (1–9), age, and RSI are depicted in Fig. 3. Sequence-specific learning was assessed by comparing fixed and random blocks (average fixed Blocks 6–8 vs. random Block 7). Analyses were run on *z*-transformed RTs, but the same analyses on raw data are summarized.

A 2 (Sequence: fixed = average of Blocks 6–8 or random = random Block 7) × 4 (RSI: 0, 250, 500, or 750 ms) × 3 (Age: 4, 7, or 10 years) mixed ANOVA was performed on mean *z*-transformed RTs. Although an SL effect is observed on Blocks 6 to 8 in Fig. 3, an illustration of the *z*-transformed

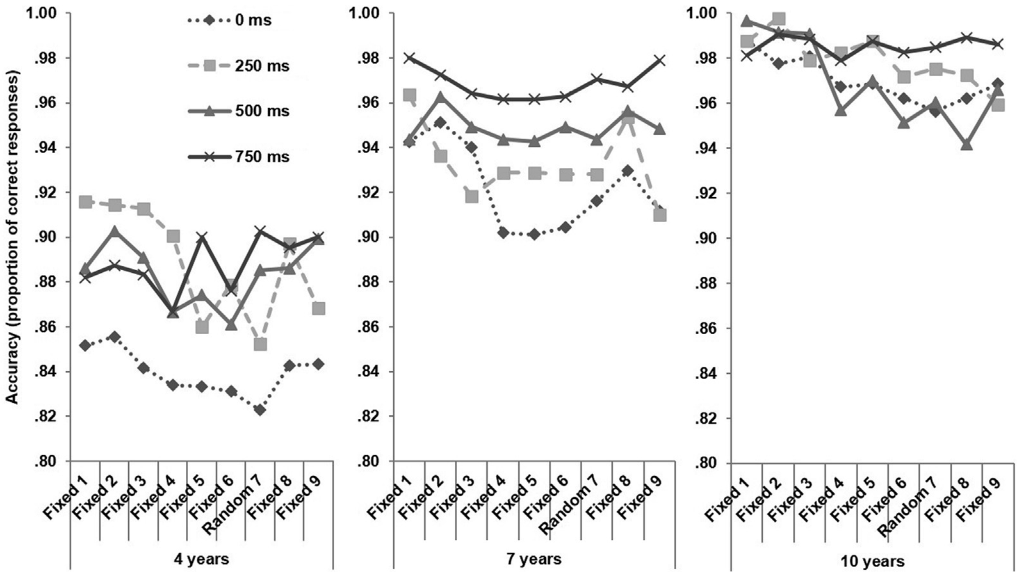

Fig. 2. Change in accuracy (proportion of correct responses) across the fixed and random blocks as a function of age (4, 7, or 10 years) and response-to-stimulus interval (RSI; 0, 250, 500, or 750 ms).

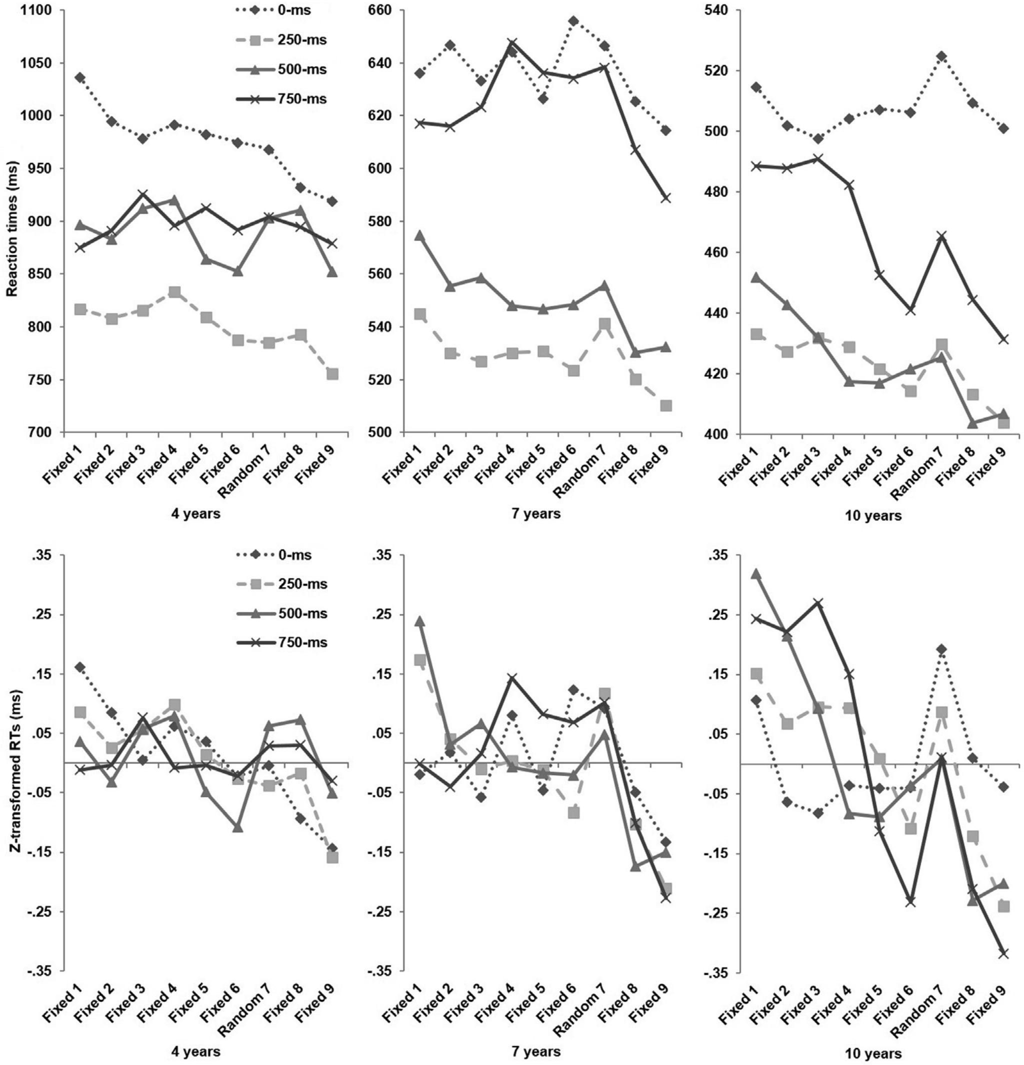

Fig. 3. Raw and *z*-transformed reaction times (RTs) across the fixed and random blocks as a function of age (4, 7, or 10 years) and response-to-stimulus interval (RSI; 0, 250, 500, or 750 ms). The error bars correspond to standard errors.

sequence-specific learning effect (random Block 7 minus average of Blocks 6–8) as a function of age and RSI can be found in Fig. 4. There was a significant effect of sequence, $F(1, 275) = 45.79$, $p < .001$, $\eta_p^2 = .14$, revealing SL. This learning effect interacted with age, $F(2, 275) = 6.75$, $p < .001$, $\eta_p^2 = .05$, with the magnitude of learning increasing with age. However, the Sequence × RSI interaction was not significant, nor was the Sequence × RSI × Age interaction (Fs < 1). Follow-up analyses using one-tailed *t* tests were performed to compare *z*-normalized RTs between fixed and random blocks as a measure of sequence-specific learning, and a Bonferroni correction was applied to address the problem of multiple comparisons (12; corrected alpha threshold: .05 / 12 = .004). Results revealed that the 4-year-old children failed to show any SL effect whatever the RSI condition [0 ms: $t(29) = 1$, $p = .17$; 250 ms: $t(21) = -0.30$, $p = .38$; 500 ms: $t(17) = 1.02$, $p = .16$; 750 ms: $t(24) = 0.32$, $p = .38$], the 7-year-old children showed a significant learning effect only in the 250-ms condition [0 ms: $t(26) = 0.90$,

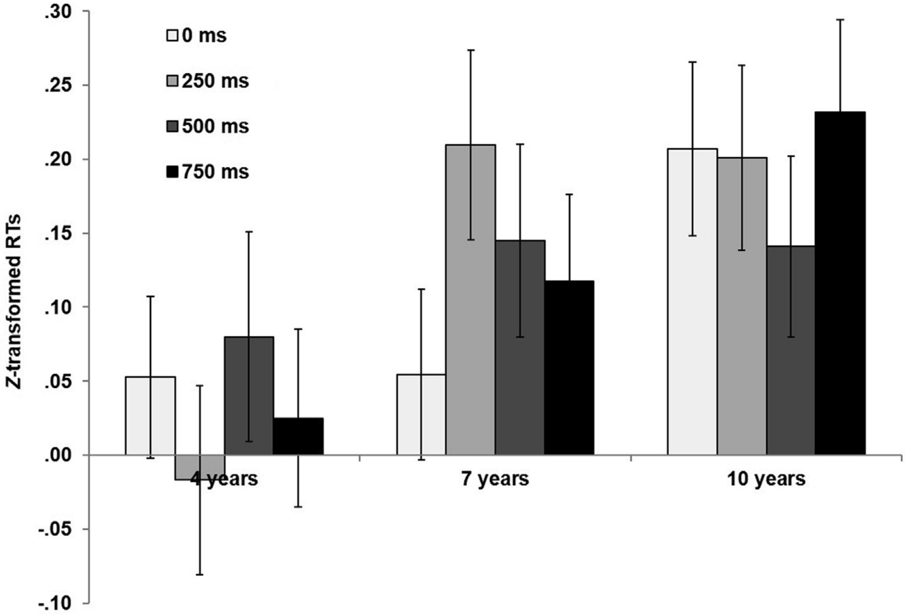

Fig. 4. *Z*-transformed learning effect (random Block 7 minus average fixed Blocks 6 and 8) as a function of age (4, 7, or 10 years) and response-to-stimulus interval (RSI; 0, 250, 500, or 750 ms). The error bars correspond to standard errors. RTs, reaction times.

$p = .19$; 250 ms: $t(21) = 3$, $p < .001$; 500 ms: $t(20) = 2.43$, $p = .01$; 750 ms: $t(25) = 2.16$, $p = .02$], and the 10-year-olds learned the sequence in all the conditions except the 500-ms RSI condition [0 ms: $t(25) = 4.05$, $p < .001$; 250 ms: $t(22) = 3.51$, $p < .001$; 500 ms: $t(23) = 2.06$, $p = .02$; 750 ms: $t(22) = 5.19$, $p < .0001$].

Comparable effects were observed when the same analyses were conducted using raw RTs. Results revealed main effects of sequence, $F(1, 275) = 9.05$, $p = .002$, $\eta_p^2 = .03$, age, $F(2, 275) = 293.06$, $p < .001$, $\eta_p^2 = .68$, and RSI, $F(3, 275) = 14.08$, $p < .001$, $\eta_p^2 = .13$, but no two-way or three-way interaction effect was significant (*p*s > .36). A follow-up analysis with *t* tests to compare raw RTs between fixed and random blocks (corrected alpha threshold: $p = .004$) revealed no SL for the 4-year-olds irrespective of RSI condition [0 ms: $p = .42$; 250 ms: $p = .75$; 500 ms: $p = .42$; 750 ms: $p = .78$], SL only in the 250-ms RSI condition for the 7-year-olds [0 ms: $p = .57$; 250 ms: $p = .003$; 500 ms: $p = .03$; 750 ms: $p = .03$], and marginal SL for 0 ms, SL for 250 and 750 ms, but no SL for 500 ms for the 10-year-olds [0 ms: $p = .005$; 250 ms: $p = .001$; 500 ms: $p = .06$; 750 ms: $p < .001$].

Conscious awareness of the sequence

To assess conscious awareness of the sequence as a function of age and RSI, the mean proportion of successions of two and three locations corresponding to the fixed sequence produced following inclusion or exclusion instructions (see Fig. 5) was compared with the theoretical proportion to produce correct successions of two and three locations at chance.

After the application of a Bonferroni correction to address the problem of multiple comparisons (24; corrected alpha threshold: .05 / 24 = .002), one-sample *t* tests revealed that successions of two locations corresponding to the fixed sequence under inclusion instructions were produced above chance level only by the 10-year-old children in the two longest RSI conditions, 500 and 750 ms, $t(23) = 6.35$, $p < .001$ and $t(22) = 3.63$, $p = .001$, respectively. Correct successions of two locations were not produced below chance level following exclusion instructions whatever the age group and the RSI

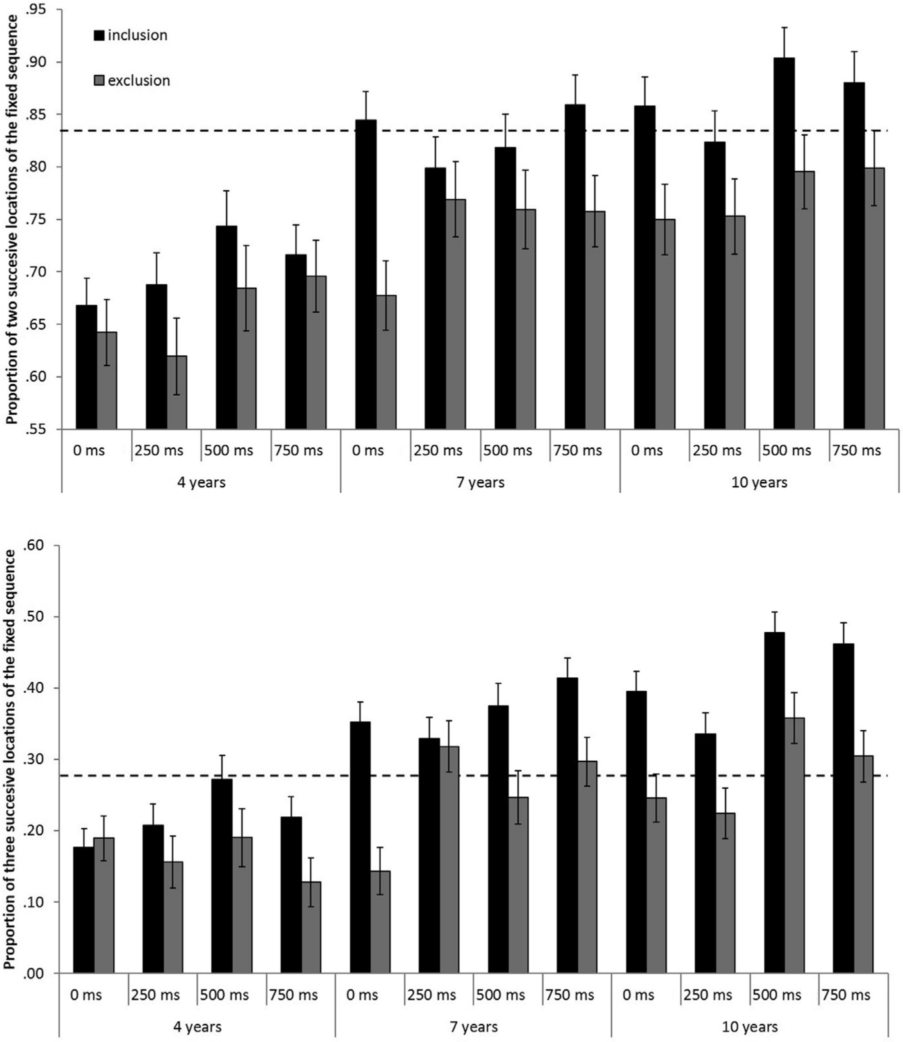

Fig. 5. Proportion of successions of two and three locations of the fixed sequence produced under inclusion and exclusion instructions as a function of age (4, 7, or 10 years) and response-to-stimulus interval (RSI; (0, 250, 500, or 750 ms). The broken line represents chance threshold (83.33% and 27.78%, respectively), and the error bars correspond to standard errors.

condition. The same analyses were conducted on the observed proportion of successions of three locations from the sequence and revealed similar results. Three-element chunks corresponding to the sequence were produced above chance under inclusion instructions only by the 10-year-old children in the two longest RSI conditions, 500 and 750 ms, $t(23) = -3.88$, $p < .001$ and $t(22) = -5.06$, $p < .0001$, respectively. Correct three-element chunks under exclusion instructions were produced significantly below chance only by the 4-year-old children in the 750-ms condition, $t(24) = -7.64$, $p < .0001$. However, this group also performed below chance under inclusion instructions, $t(24) = -3.89$, $p = .005$.

To summarize, inclusion performance, but not exclusion performance, suggests that conscious awareness about the sequence emerged only for the 10-year-olds faced with extended 500- and 750-ms RSI because two and three successive locations were produced above chance under inclusion instructions only in these experimental conditions.

Discussion

This study investigated the effect of RSI on the implicit SL of children aged 4, 7, and 10 years by systematically manipulating the RSI (0, 250, 500, or 750 ms). As expected, accuracy increased with age and with longer RSI, but the two factors did not interact and the accuracy scores remained high in all conditions. Analyses of raw and *z*-normalized RTs revealed that the 10-year-olds exhibited SL in all temporal conditions except the 500-ms RSI condition, whereas the 7-year-olds learned the sequence only in the 250-ms RSI condition and the 4-year-olds failed to learn the sequence whatever the RSI. Finally, the results suggest that conscious awareness emerged in the older children, but only when the sequence was presented with 500- and 750-ms RSIs. The discussion questions the robustness of implicit learning processes with regard to possible interactions between individual and contextual factors.

Although the effect of RSI has never been tested systematically in a developmental perspective, the ability to learn temporal patterns in sequenced actions has been investigated in elementary-school-age children (Shin, 2011). Using an SRT task, in which a response (locations) and a timing (RSI) sequence were presented repeatedly in a phase-matched manner to 6- to 13-year-old children and young adults, the author observed that integrative learning (of response and timing sequences) increased with age in the children. In addition, the results indicated that temporal learning develops with age and that executive functions and processing speed play a critical role in the acquisition of temporal patterns of actions. Previous research has already shown that processing speed correlates with performance on implicit SL tasks (Kaufman et al., 2010; Salthouse et al., 1999). In addition, previous studies that have manipulated RSI in adults suggested that the short-term memory capacity and the level of activation of the to-be-learned elements supported SL (Frensch & Miner, 1994) and that the quality of the representation of the stimuli affected the knowledge of the sequence (Destrebecqz & Cleeremans, 2001, 2003). Experimental conditions that artificially reduce the opportunity to process successive elements simultaneously (longer RSIs) or to develop high-quality memory traces (no RSI) would negatively affect SL and a fortiori for participants whose capacity limits are reached. Because executive functions, processing speed, attentional resources, and working memory span develop with age (e.g., Diamond, 2013; Gathercole, 1999; Hitch & Halliday, 1983; Kail, 1991), we hypothesized that tolerance to a larger range of RSIs (shorter and longer than the standard RSIs of 250 and 500 ms) should appear with age. In the current study, presumed effects of this developing tolerance to temporal factors were observed across different measures of learning, namely specific-sequence learning effect and conscious awareness of the sequence per se.

Sequence-specific learning as a function of age and RSI

Our experiment aimed at determining whether the participants became sensitive to the sequence and whether SL depended on individual and contextual factors such as age and RSI. Our assumption was that the children became more resilient to temporal constraints with age and still learned the sequence when RSI was shortened or lengthened compared with the more conventional 250- and 500-ms RSI conditions. The results showed that the 10-year-olds exhibited SL in all temporal conditions except the 500-ms condition, whereas the 7-year-olds learned the sequence only in the 250-ms RSI condition. Note, however, that although RTs did not decrease during the learning phase for the 0- and 750-ms RSIs at 7 years of age and did not reveal the classic learning curve, the learning curve is more conventional for the 500-ms RSI, as it was for the 10-year-olds despite a lack of significant learning effect. Finally, SL was not observed for the youngest children whatever the RSI condition. It is important to note that the results were similar irrespective of whether SL was measured on raw or *z*-normalized RTs. This level of consistency suggests that our observations are not artifacts due to the dependent variable used to assess learning.

The results support the assumption that development brings with it better adaptation to temporal constraints during an implicit learning episode given that the oldest children showed SL for three of the four tested temporal conditions, including the extreme ones (0 and 750 ms), whereas the 7-year-olds did not learn the sequence when the RSI was lengthened (500 and 750 ms) or shortened (0 ms) relative to the 250-ms RSI. The performance of the 7-year-olds suggests that different abilities develop and allow adaptation to temporal constraints during SL. First, low processing speed at 7 years of age did not make it possible to prevent the overlap between the processing of successive elements that were presented too fast (0-ms RSI). This result is consistent with previous results reporting that processing speed correlates with performance on tasks of implicit SL (Kaufman et al., 2010; Salthouse et al., 1999) and plays a critical role in the acquisition of temporal patterns of actions (Shin, 2011). Second, attention and working memory span are probably not mature enough at 7 years of age to tolerate an increase in the time between the elements to be associated (at least for 750 ms). This is consistent with Frensch and Miner's (1994) theoretical framework. According to the authors, lengthening RSI reduces the number of simultaneously activated to-be-learned elements in short-term memory and affects SL. Although this last RSI condition did not reveal the classic learning curve (decrease of RTs between Blocks 1 and 6), RTs decreased dramatically for the fixed Blocks 8 and 9 following the introduction of the random sequence. This suggests that a boredom effect may have masked learning until the introduction of the random Block 7 that rekindled the participants' interest in the task and revealed a learning effect. Finally, the youngest children did not exhibit SL whatever the RSI condition, including the conventional 250- and 500-ms conditions. This result, coupled with the absence of learning for three of the four conditions in the 7-year-olds, conflicted with the postulate that implicit learning capacities are age independent (Reber, 1993). Previous studies using an SRT task, however, reported that children aged 6 to 10 years and adults showed the same learning pattern (Meulemans et al., 1998). This result has been extended to 4-year-old children (Thomas & Nelson, 2001), and knowledge of a repeated sequence was also reported in children as young as 2 years (Bremner et al., 2007). Because the sequence was the same as that used in Meulemans et al. (1998) and an optimal 250-ms RSI was included among our experimental conditions, the reason why we failed to demonstrate learning in our 4-year-old participants relates to other dimensions of the task. Comparing our procedure with that of Thomas and Nelson (2001), both used a tactile tool rather than a button box, thereby avoiding the difficulty for young children to understand the symbolic correspondence between the stimulus locations and the response buttons (Thomas & Nelson, 2001). A possible fatigability effect, which is more likely to occur in young children, may have masked the learning effects. However, our learning phase (360 trials) was quite similar to that used by Thomas and Nelson (300 trials). In addition, half-block analysis did not reveal a different pattern of results. Nevertheless, the assumption of a boredom effect cannot be totally excluded for the 750-ms condition given that the RTs between Blocks 1 and 6 for the 4- and 7-year-olds did not decrease. However, this assumption cannot account for the absence of learning in the standard 250-ms RSI condition in the 4-year-olds. A more noticeable difference between our procedure and that of Thomas and Nelson (2001) relates to the spatial arrangement of the localizations. In Thomas and Nelson's experiment investigating SL in 4-year-olds, a quadrant presentation was used rather than a linear presentation. Successive elements of the sequence could be easier to associate in this configuration. Spatial distance among the four locations was equivalent in the quadrant presentation, and this presentation mode probably required less attention shifting than the classical linear presentation. In this view, a further study should investigate whether young children are more sensitive to spatial constraints than older children during SL.

Emergence of conscious awareness of the sequence as a function of age and RSI

In this section, we question whether temporal factors like RSI affected explicit knowledge about the sequence. To assess conscious awareness of the sequence, the participants were asked to reproduce the sequence they often encountered during the task by showing the mole movements they believed had occurred frequently. This task was adapted from Jacoby's (1991) PDP. The number of correct successions of two and three locations of the fixed sequence produced under inclusion suggested that conscious awareness of the sequence emerged only in older children confronted with sufficiently long RSIs (500 and 750 ms). However, this claim must be seen in the light of the fact that correct successions were not produced below chance in these experimental conditions under exclusion instructions. This finding nevertheless suggests that RSI manipulations do not affect only RT-based measures of sequence-specific learning but also affect the capacity to consciously access the knowledge of the sequence. Destrebecqz and Cleeremans (2001, 2003) reported that adults trained with a 0-ms RSI did not develop any conscious knowledge of the sequence, whereas training with longer RSIs allowed the development of conscious awareness of the sequence because the time available to process the stimuli affects the quality of the representation of the sequential constraints and thus the knowledge of the sequence. Our results suggest that this conclusion could be extended to children from at least 7 to 10 years of age. However, our results conflict with those of previous studies reporting conscious awareness of the sequence in 0- and 250-ms RSI conditions (Norman et al., 2006; Shanks et al., 2003, 2005; Wilkinson & Shanks, 2004) and no increase in conscious knowledge with an extended (500-ms) RSI (Rünger, 2012). However, it is worth noting that these studies were run in adults with different RSI variants and different measures of conscious awareness (e.g., recognition task) (see Perruchet & Pacteau, 1990, for criticisms of the use of recognition tasks as measures of conscious awareness), in addition to other sources of variation (e.g., complexity of the sequence; number of blocks, repetitions, and trials). Moreover, conscious awareness of the sequence did not seem to be associated with learning performance in our study. Previous studies have suggested that sequence learning tasks could benefit from the explicit knowledge acquired by the participants in the tasks (e.g., Curran, 1997; Curran & Keele, 1993). In the light of these results, performance should have been better for the older children in the longer RSI conditions, in which conscious awareness emerged. A first possibility is that this result reveals a genuine implicit/explicit dissociation, as suggested by Meulemans et al. (1998). Second, the link between explicit knowledge and performance is probably less clear in children than in adults because children are less able to use their explicit knowledge to improve their performance (e.g., Witt et al., 2013). An alternative explanation is that long RSIs have different effects on the measures related to the implicit learning of the sequence and those related to the conscious awareness of the sequence. In addition, our procedure for assessing explicit knowledge may be inappropriate for capturing information to which children have access. Our inclusion/exclusion task was, however, based on a procedure that successfully revealed cognitive control of sequential knowledge in children as young as 2 years (Bremner et al., 2007). Further studies should meet the challenge of providing valid measures of explicit awareness in young children whose verbal skills are still developing.

Limitations

Before concluding, we need to address an important limitation of the current experiment, namely that classic measures of processing speed and short-term/working memory could have been added to our experiment in order to run correlations between these measures and learning measures, as was done by Frensch and Miner (1994). However, constraints relating to school organization during the experiments made it impossible to administer additional assessment batteries. In addition, our age range included preschoolers, and assessing these processes in this age range is a significant challenge. Most conventional span-based working memory measures are given only to children aged 6 years and older, and tests normed for 4- to 5-year-olds often suffer from floor effects or reveal increasing performance with age but no significant age differences in this age range. Younger children are also more susceptible to interference effects due to their limited attentional control and language comprehension (Roman et al., 2014). The same observations apply to the assessment of processing speed in very young children when we consider the possible but challenging use of the subtests of the Wechsler scales (Coding, Cancellation, and Symbol) or Nouvelle Échelle Métrique de l'Intelligence (NEMI-2; speeded naming test). However, further studies should address this issue, at least in children aged 6 years and older, by adding batteries designed to assess these processes using carefully selected RSIs or task load situations in order to investigate the role of these processes in children's SL. We would expect correlations to emerge, in particular, between learning and processing speed in time-constrained situations, such as in the absence of RSI, whereas correlations between learning and short-term/working memory should emerge for longer RSIs. In addition, both cognitive processes should correlate with learning measures in a dual-task condition.

Conclusion

Our results suggest that implicit SL in children is influenced by temporal factors such as RSI, which interacts with age. The fact that SL in the 7-year-old children was more impaired when the RSI was shortened than when it was lengthened argues for the critical role of processing speed in the acquisition of sequenced actions, in accordance with previous results (Kaufman et al., 2010; Shin, 2011). In addition, conscious awareness of the sequence seems to be influenced by RSI, at least in older children, extending to children results previously observed in adults (Destrebecqz & Cleeremans, 2001, 2003). We also revealed that SL remained difficult to observe in young children (4 years). Differences between our procedure and one that succeeded in revealing SL in children aged 4 years (Thomas & Nelson, 2001) suggest that temporal constraints are not the sole factor mediating SL and instead argue for the potential role of spatial constraints (linear vs. quadrant presentation). Thus, the results suggest that the capacity to adapt to temporal constraints, and potentially to spatial constraints, is critical in the ability to learn a repeated pattern that governs a visual or visuomotor sequence. The role of these factors needs to be investigated in further studies and linked with psychological measures of processing speed and executive functions. Finally, the current study suggests that special attention should be paid to temporal and spatial features when designing learning situations, especially when these learning situations are intended for young children, who may find it difficult to adapt to temporal and spatial constraints because of immature processing speed and reduced attention/working memory span.

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