

From domain-specific to domain-general?

The developmental path of metacognition for strategy selection

Metacognition, typically defined as the ability to evaluate (or monitor) and regulate (or control) the success of cognitive processes (Dunlosky & Metcalfe, 2009), has been regarded as a fundamental skill influencing cognitive performance and learning in domains as diverse as arithmetic, memory, reading, perception, and many others (Kuhn, 2000). Generally, metacognition is viewed as a global ability that is correlated across content domains, suggesting that participants who are good at evaluating their performance for one sort of task also tend to be good at evaluating their performance for another sort of task (Schraw, Dunkle, Bendixen, & Roedel, 1995).

Domain-General or Domain-Specific Metacognition Processes?

In adults, the assumption that metacognition is domain-general is supported by two types of evidence. First, a number of behavioral studies seem to indicate that inter-individual differences in measures of metacognitive sensitivity (i.e., how well one can discriminate between correct and incorrect responses through the monitoring of one's own performance) correlated across unrelated cognitive tasks (e.g., Gardelle & Mamassion, 2014; McCurdy et al., 2013; Schraw et al., 1995; Song et al., 2011; Veenman, Elshout, & Meijer, 1997; Veenman, Prins, & Verheij, 2003). Second, imaging data suggest that adults' metacognitive abilities for different types of tasks partially depend on common neural structures (Allen et al., 2016; Anderson, Betts, Ferris, & Fincham, 2011; McCurdy et al., 2013; Shimamura, 2000). These results, however, have to be qualified to some extent. Indeed, behavioral correlations observed across domains have been shown to depend on the type of metacognitive measures used as well as on whether the performance at the cognitive level is controlled (e.g., Kelemen, Frost, & Weaver, 2000). Furthermore, some imaging studies have failed to find common neural structures when examining adults' metacognitive abilities across domains (e.g., Baird, Smallwood, Gorgolewski, & Margulies, 2013).

In children, the situation is even less clear. Indeed, most experiments testing metacognition in children have been conducted in a single cognitive domain at a time (see Schneider & Löffler, 2016, for an overview). Only a limited number of studies have examined the developmental trend of metacognitive skills concurrently across several domains. The few available data sets suggest that metacognition (understood here as metacognitive sensitivity or monitoring) could be domain-specific early in development and generalize across domains as children mature (Lyons & Ghetti, 2010; Schraw & Nietfeld, 1998; Veenman & Spaans, 2005; Vo, Li, Kornell, Pouget, & Cantlon, 2014). For example, Vo et al. (2014) have shown that 5- to 8-year-olds' metacognition for a numerical discrimination task was unrelated to their metacognition for an emotion discrimination task. Moreover, Veenman and Spaans (2005) found that metacognition correlates between domains at age 15. These results suggest that a shift from a domain-specific to a domain-general metacognition could occur between these ages. To date, however, this hypothesis has never been directly tested.

Determining the developmental trajectory of whether and how metacognition generalizes across domains could be crucial in at least two respects. From a theoretical perspective, this would shed new light on how metacognition develops throughout childhood while helping us to improve our understanding of both the functioning and the cognitive architecture of metacognitive processes. From a practical perspective, determining when metacognition becomes domain-general and thereby the conditions for such a generalization could have a major impact on metacognitive revalidation programs. Indeed, if metacognition does not depend on domains, it implies that metacognitive interventions in one domain (e.g., arithmetic, memory, or reading) could have positive effects across all domains. For these reasons, the first aim of the present study was to examine age-related differences in the relations between measures of metacognitive sensitivity for two different cognitive tasks in children aged from 8 to 13 years. Specifically, participants were asked to evaluate their performance on a strategy selection task in two independent cognitive domains: arithmetic and memory.

Metacognition and Strategy Selection

Several decades of research in children (see Siegler, 1996, 2007, for overviews) and during adulthood (see Lemaire, 2016, for an overview) have shown that people use a variety of strategies to accomplish cognitive tasks. This plethora of studies indicates that participants' performance and age-related changes in cognitive performance depend on strategies. Yet, despite extensive research seeking to understand how people choose among strategies on a given item (e.g., Metcalfe, & Campbell, 2011; Thevenot, Fanget, & Fayol, 2007), participants' ability to monitor their chance of selecting the better strategy in the future (i.e., prospective judgment) or to estimate their level of confidence associated with a selected strategy (i.e., retrospective judgment) has been examined neither in the arithmetic domain nor in the memory domain. As four decades of studies – mainly in the memory domain – have established that the influence of metacognitive processes on cognitive performance is exerted through the implementation of effective strategies (e.g., DeMarie, Miller, Ferron, & Cunningham, 2004; Geurten, Lejeune, & Meulemans, 2016; Nelson & Narens, 1990; see Dunlosky & Metcalfe, 2009 for an overview), it is surprising that so little has been done to investigate how accurate participants are in estimating whether they selected (or will select) the most effective strategy on a given item. Some data suggest that both adults and children can use better strategy judgments to change strategy while executing an already-selected strategy (e.g., Ardiale & Lemaire, 2012; Ardiale & Lemaire, 2013; Siegler & Crowley, 1994). For example, Ardiale and Lemaire asked children and adults to execute pre-selected arithmetic strategies on arithmetic problems. After participants started to execute cued strategy for 1 sec. (too short to fully complete strategy execution), they were asked to judge whether the cued strategy was the better or poorer strategy for that problem. They were also given the possibility to switch strategy in case they judge the cued strategy to be the poorer strategy. Data showed that children provided better strategy judgments and switched more and more often as they grew older. Note however that one important limitation of Ardiale and Lemaire's work is that children's better strategy judgments were not based on children's strategy selection but on strategies selected by the experimenter. Unknown is how

children monitor their chances of selecting the better strategy on each item and how such strategy monitoring changes with age.

In the arithmetic field, some theoretical assumptions made by computational models of strategy selection are consistent with the hypothesis that being able to introspect on how easy it would be to select the better strategy or on the level of uncertainty associated with the selected strategy increases the likelihood to be better at choosing the best strategy on each item. Generally, computational models propose that choosing among multiple strategies crucially involves associative mechanisms such as activating the relative costs/benefits of each strategy and selecting the strategy that works best for a given problem on the basis of problem and strategy characteristics (e.g., Lovett & Anderson, 1996; Siegler & Shipley, 1995; Lovett & Schunn, 1999; Neches, 1987; Rieskamp & Otto, 2006; Siegler & Araya, 2005). In addition to associative mechanisms, two of the existing computational models assume that strategy choices involve metacognitive mechanisms. Specifically, in the Lovett and Schunn's (1999) Represent, Construct, Choose, Learn model (RCCL), the metacognitive system enables participants to interrupt a strategy mid-execution if they estimate that the current strategy is not the best one or if it is inappropriate. In Siegler and Araya's (2005) Strategy, Choice, and Discovery Simulation* (SCADS*), the metacognitive system is crucial to create or discover new strategies. In sum, models of strategies include metacognitive processes to evaluate the strategies once selected and, possibly to interrupt strategies mid-execution to switch for a better strategy (RCCL) or to create and discover new legitimate strategies (SCADS).

In this context, the second aim of the present study was to examine metacognitive sensitivity for strategy selection at different ages in two unrelated cognitive domains. Our goal was to investigate whether children are able to make accurate metacognitive judgments on strategy selection and whether there are age-related changes in metacognitive sensitivity for both the arithmetic and the memory tasks. If observed, this pattern would indicate that metacognition for strategy selection improves with age, providing a necessary prerequisite for the hypothesis that

metacognition accounts for age-related differences in children's strategy selection in both the arithmetic (e.g., Lemaire & Callies, 2009; Lemaire & Lecacheur, 2011) and the memory fields (e.g., Ghatala, 1986; Son, 2005).

Overview of the Present Study

The primary goals of this study were to document the developmental course of domain-general/-specificity of metacognition by examining the ability of children to monitor the accuracy of their strategy selection in both the arithmetic and the memory domains. To test domain-general versus domain-specific metacognition processes during strategy selection, three experiments were conducted. In each experiment, three groups of children aged of 8-9, 10-11, and 12-13 years were recruited. These age groups were selected because previous studies on metacognition have suggested that a shifting from domain-specific to domain-general metacognition could occur between 8 and 15 years of age (Veenman & Spaans, 2005; Vo et al., 2014). Furthermore, important changes also occur in how children select and execute strategies between those ages (see Siegler 1996, 2007, for overviews). In all previous studies exploring the hypothesis of domain-general mechanisms, metacognition was assessed by asking participants to evaluate their own cognitive performance. No research focused on how accurate participants were to judge the success of their strategy selection. Yet, monitoring the accuracy of strategy selection in different domains could possibly involve more global metacognitive skills than monitoring cognitive performance. Using strategy selection tasks could thus increase the chances of showing a trend toward generalization of metacognitive processes, if such trend exists.

For these reasons, we asked all children to accomplish two better strategy selection tasks. In the arithmetic task, participants were given arithmetic problems (e.g., $47+32$) and had to select the better strategy to solve each of them among two available strategies, namely, a rounding-down strategy (doing $40+30=70$) or a rounding-up strategy (doing $50+40=90$). In the memory task, participants were given triads of words (e.g., *Bat – Cat – Hat*) and had to select the better strategy to

remember triads among two available strategies, namely, a phonological strategy (words ending = “AT”) or a semantic strategy (e.g., “Animal”). Asking participants to select among a set of strategies enabled to control for individual differences in strategy repertoire (e.g., some children know and use more strategies than others). Also, previous works have shown that when children are left free to choose whichever strategies they want to accomplish these tasks, they do use the above mentioned strategies spontaneously (e.g., Bjorklund, Dukes, & Brown, 2009; LeFevre, Greenham, & Waheed, 1993; Lemaire, Lecacheur, & Farioli, 2000). Designs controlling the number of available strategies to choose among do not yield different findings regarding age-related changes in rates of better strategy selection and in strategy performance.

In Experiment 1, metacognition was assessed using Ease of Selection judgments (EoS). Specifically, in both the arithmetic and the memory tasks, children were asked to judge on a trial-by-trial basis the ease with which they would select the better strategy (i.e., prospective judgments). In Experiments 2 and 3, metacognition was assessed using Retrospective Confidence Judgments (RCJ). For each task, children were asked to estimate on a trial-by-trial basis the level of confidence associated with their responses (i.e., retrospective judgments). This procedure was used because several studies have shown that some aspects of prospective metacognitive judgments (i.e., prediction of future performance) differ from retrospective metacognitive judgments (i.e., estimation of the accuracy of past responses) (Kelemen et al., 2000; Siedlecka, Paulewicz, & Wierzchoń, 2016). For instance, Kelemen et al. (2000) showed no significant correlations between these different types of judgments within the same domain in adults while several studies in children have revealed differences in their developmental trajectories (see Schneider & Lockl, 2008, for an overview). Also, neuropsychological dissociations have previously been found between prospective and retrospective judgments in adults with acquired brain injury (e.g., Pannu & Kaszniak, 2005), suggesting that these metacognitive tasks may partially depend on dissociable neural substrates (but see Chua, Schacter, & Sperling, 2008).

To measure metacognitive sensitivity, different approaches are available. From a statistical perspective, each of them has unique strengths and weaknesses (for a detailed description of the characteristics of these metacognitive metrics, see Fleming & Lau, 2014). To provide a reliable picture of children's metacognitive abilities, we computed three measures of metacognition for each strategy selection tasks: ϕ , γ , and A'_{ROC} . The ϕ and γ coefficients are popular measures of metacognitive sensitivity and provide a common scale to compare our results to those of previous studies examining the domain-generalty of metacognition. However, these two measures may be influenced by the tendency to use higher or lower confidence ratings (bias). The A'_{ROC} index provides a bias-free measure of metacognition (Galvin, Podd, Drga, & Whitmore, 2003).

We predicted that metacognitive sensitivity should be higher than chance for both the arithmetic and the memory tasks, indicating that children can introspect on their strategy choices. Furthermore, we also expected that metacognition for strategy selection should increase with age. Regarding the hypothesis of a developmental trend in metacognition across domains, several scenarios are possible. First, metacognition is domain-specific in childhood and remains that way through adulthood. In this case, no covariations should be found between metacognitive measures for the two strategy selection tasks. However, given the amount of data indicating that metacognition correlates across domains in adulthood, this hypothesis is quite unlikely. Second, there is an embryonic domain-general metacognition in children that increases with age. In this case, significant relations should be found between metacognitive measures in all children, and these relations should be larger in older children. Third, metacognition shifts from domain-specific to domain-general. In this case, we expected no significant covariations between metacognitive measures for the two strategy selection tasks in younger children, but significant relations in older participants. This pattern would provide strong evidence for the hypothesis that metacognition evolves from domain-specific to domain-general during childhood.

Experiment 1

The aim of Experiment 1 was to examine the possible transition from domain-specific to domain-general metacognitive processes during childhood using a common prospective metacognitive task. Specifically, participants were instructed to estimate the ease with which they would select the better strategy on a given item before actually selecting it. This type of judgment is commonly used to assess people's ability to monitor their cognitive processes (Dunlosky & Metcalfe, 2009) and is generally shown to be sensitive to developmental changes in children's metacognitive skills (see Schneider & Lockl, 2008).

Method

Participants. The final sample included 60 typically developing children aged 8-9 (grade 5; $n = 20$; 10 females; mean age = 9.1 years; $SD = 0.59$), 10-11 (grade 6; $n = 20$; 10 females; mean age = 10.9 years; $SD = 0.47$), and 12-13 (grade 7; $n = 20$; 10 females; mean age = 12.6 years; $SD = 0.55$) years. The native language of all children was French, and all children were from a middle- to upper-class socioeconomic status. Three additional participants were tested but excluded from the final analyses because they used the same strategy on all items in the arithmetic task. No group differences were found regarding parental education and non-verbal intelligence ($F_s < 1.5$, respectively assessed using both parents' years of education and scores on the Matrix Reasoning test; Wechsler, 2004). The sample was recruited from elementary and middle schools in Belgium. Data collection stopped when the number of participants was sufficient to reach a predicted power of .80 for a within-between interaction (medium effect size).

Stimuli. The stimuli for the arithmetic task were 40 two-digit addition problems (e.g., $32 + 47$). Based on previous findings in arithmetic (see Kadosh & Dowker, 2015, for an overview), the following factors were controlled: (a) no operand had a 0 or a 5 unit digit, (b) digits were not repeated within operands (e.g., $33 + 42$), (c) digits were not repeated in the same unit or decade positions across operands (e.g., $62 + 67$), (d) no reverse order of operands was used (e.g., $56 + 23$ vs. $23 + 56$), (e) the first operand was larger than the second operand in half the problems, and (f) the

operand with the smallest unit digits was in the left position in half the problems (e.g., $42 + 36$) and in the right position in the other problems (e.g., $23 + 41$). Moreover, to avoid ceiling effects and make the selection task more difficult, all problems had the unit digit of one operand smaller than 5 while that of the other operand was larger than 5 (e.g., $32 + 49$). Mean correct sums were 67.1 (range = 42–82). Half the problems ($N = 20$) were so-called rounding-down problems because they were best estimated (i.e., closest sums from the correct sums) with the rounding-down strategy (e.g., $56 + 21$) and half rounding-up problems because they were best estimated with the rounding-up strategy (e.g., $24 + 39$). Mean correct sums were 66.2 (range = 42–79) for rounding-down problems and 65.8 (range = 42–82) for rounding-up problems. The 40 problems were grouped into 20 pairs. Each pair was followed by a countdown task (i.e., counting backward from a particular number by 3). Half of the pairs were composed of the same type of problems (e.g., a rounding-down problem followed by a rounding-down problem) while the other half included different types of problems (e.g., a rounding-down problem followed by a rounding-up problem). This method was used because previous data showed strategy switch costs (Lemaire & Brun, 2016) that decreased with children's age. We thus wanted to control the influence of switching from one type of problems to the other on children's strategy selection and metacognitive sensitivity.

The stimuli for the memory task were 40 triads of French words (e.g., *Dog – Frog – Bee*). All words were selected to be included in the vocabulary of 8 year olds (Lachaud, 2007). Half the triads ($N = 20$) were so-called phonological triads because they were composed of words that were phonologically related (e.g., *Bat – Cat – Hat*) and, thus, were more likely to be remembered with the help of a phonological cue (e.g., “word ending = AT”). The other triads were so-called semantic triads because they were composed of words that were semantically related (e.g., *Dog – Frog – Bee*) and, thus, were more likely to be remembered with the help of a semantic cue (e.g., “animal”). The words composing these two types of triads were matched on frequency (6.14 vs. 6.05 occurrences per million words; Radeau, Mousty, & Content, 1990), number of syllables (means of 1.65 vs. 1.68 syllables), and concreteness (values of 6.28 vs. 6.44; Desrochers & Bergeron, 2000). Moreover, each

triad included two words that were both phonologically and semantically related (e.g., *Cat – Bat* or *Dog – Frog*) in such a way that the better strategy had to be determined on the basis of the third word (e.g., *Hat* or *Bee*), which was either phonologically or semantically related to the other two words. The position of that words within triads was counterbalanced across triads. This method was employed to avoid ceiling effects and to make the selection task more difficult. Finally, the 40 triads were grouped into 20 pairs. Each pair was followed by a countdown task. Half of the pairs were composed of the same type of triads (e.g., a phonological triad followed by a phonological triad) while the other half including different types of problems (e.g., a phonological triad followed by a semantic triad).

Procedure. Institutional Review Board approval was obtained from the local ethics committee before data collection began (protocol number: 1617-01). Written consent was obtained from children’s parents before the study. Children were individually tested in a quiet room in their school using a laptop computer equipped with Toolbook 11.5 software. They underwent a 60-minute session including an arithmetic and a memory tasks which were separated from each other by a 2-minute break. Half the children completed the arithmetic task first, and the other children did the memory task first.

Following previous studies testing children’s computational estimation skills (e.g., Lemaire & Brun, 2014, 2016), in the arithmetic task, children were asked to give an approximate answer to each arithmetic problem that is as close as possible to the correct answer without actually calculating the correct answer. To this end, they were instructed to select between rounding both operands down (rounding-down strategy) and rounding both operands up (rounding-up strategy) on each problem. The two strategies were illustrated with a couple of examples. The better strategy for a given problem was the strategy that yielded the answer that was closest to the correct product for this problem. Instructions emphasized that participants should not use the mixed-rounding strategy (i.e., rounding one operand down and the other up to the closest decades) and should do nothing more than the initial rounding down or up (i.e., adding or subtracting small amounts after calculating the

sum of rounded operands). All participants were presented the 20 pairs of problems in random order.

In the memory task, stimuli were presented triad-by-triad. Following previous studies examining children's associative memory skills (Geurten, Willems, & Meulemans, 2015), children were asked to remember as many triads as possible in order to recall them when the first word of each triad would be presented later. To this end, they had to select between generating a phonological cue (phonological strategy) or a semantic cue (semantic strategy). The strategies were illustrated using a couple of examples. The better strategy for a given triad was the strategy that helped children to link the three words of the triad together. Instructions emphasized the fact that participants should not use any other strategy than the two available strategies and should do nothing more than generating the cue (i.e., using another memory strategy). All participants were presented with the 20 pairs of triads in random order.

Each stimulus of the two tasks went through three successive phases: (a) a judgment phase, (b) a selection phase, and (c) an execution phase (for an illustration of the experimental procedure, see Figure 1). For each task (arithmetic and memory), the test was preceded by four practice trials so that children could get familiarized with the apparatus and the general procedure used in each phase. At the end of the four practice trials, all children seemed to have understood what the task required of them. The stimuli were presented in 54-point Calibri black font in the center of the computer screen. Each trial was preceded by a blank screen for 250 ms that was followed by a warning signal ("+") displayed for 500 ms.

< Figure 1 >

Judgment phase. The first step of each task was an EoS (Ease of better strategy selection) judgment. The stimuli were presented one by one in the center of the screen for 3 s each. After each stimulus display, children were instructed to indicate how easy it would be to select the better strategy (between the two available strategies) to estimate the correct sums of each problem

(arithmetic task) or to increase the likelihood of remembering each triad (memory task). A thermometer procedure based on the hot/cold game (Koriat & Shitzer-Reichert, 2002) was used to enable children to understand the meaning of EoS. Specifically, a colored horizontal thermometer appeared on the computer screen with a cursor positioned in the middle. Children were asked to give their ratings by moving the cursor anywhere from the deep blue (very cold) end to the deep red (very hot) end of the scale according to their level of estimated difficulty. The position of the cursor on the thermometer was transformed into an EoS percentage score (0%, 20%, 40%, 60%, 80%, and 100%). Specifically, the thermometer was divided into six bins. Positioning the cursor within a band translated into a specific judgment value.

Selection phase. For each item, the judgment phase was immediately followed by a strategy selection phase. The stimuli were presented together with two response buttons for an unlimited time. Each response button corresponded to one of the two available strategies (i.e., rounding-down/rounding-up or phonological/semantic). Children were required to choose which of the two strategies was the better strategy to complete the task by pressing one of the two buttons. We recorded the number of better strategy selections and mean selection times for each task. Selection times that were more than three standard deviations from the mean were excluded.

Execution phase. On each item, once the strategy was selected, participants were asked to execute it out loud. In the arithmetic task, they rounded both operands up or down before adding the rounded operands (e.g., “ $24 + 42 = 20 + 40$ ”). A correct execution was coded 1, and an incorrect execution was coded 0. In the memory task, participants generated the cue out loud (e.g., “animal”). The generation of a correct cue was coded 1, and the generation of an incorrect cue was coded 0. The experimenter pressed a response key immediately after the participant’s response (i.e., the up key was pressed if the strategy was executed correctly. The down key was pressed otherwise). We collected the number of strategies correctly executed and mean execution times for each task. Execution times that were more than three standard deviations from the mean were excluded. In the arithmetic task, children moved on to the next problem directly after executing the strategy. In the

memory task, children were asked to recall the last two words of each triad in response to the presentation of the first word (e.g., “Dog - ? - ?”) before moving on to the next triad. This procedure was used because we wanted to keep children motivated to generate cues that would help them to retrieve the items. All participants recalled all triads. No feedback was given to children following their responses in order not to interfere with participants’ ability to internally monitor their own performance by providing external information (Geurten & Meulemans, 2016).

Results

First, we examined age-related differences in strategy selection and execution for the arithmetic and memory tasks. Then, we tested children’s metacognitive sensitivity (i.e., the accuracy of EoS judgments). Finally, we tested the domain-general versus domain-specificity of metacognition. Unless otherwise noted, differences were significant to at least $p < .05$ in Experiments 1, 2, and 3. Preliminary analyses indicated that no gender or order effects were significant on any of the dependent variables. Similarly, we did not find any effects of the type of pairs on children’s performance. Finally, we conducted a Grubb’s test to check for possible outliers. No outliers were found for any of our dependent variables, all $ps > .05$.

Age-related changes in strategic variations. Mean rates of better strategy selection and mean selection latencies for the arithmetic and memory tasks were analyzed to test age-related and task-related differences in strategy selection. Mean execution times were analyzed to test strategy execution. We did not conduct analyses on the mean rates of better strategy execution because most children made no execution errors. Rates of better strategy selection, mean selection latencies, and mean strategy execution times were analyzed with mixed-design ANOVAs, 3 (Age: 8-9, 10-11, 12-13 year olds) x 2 (Task: arithmetic, memory), with age as the only between-participants factor (see means in Table 1).

< Table 1 >

Better strategy selection rates. Rates of better strategy selection increased with children's age, $F(2,57) = 4.12$, $MSe = 1.15$, $\eta^2_p = .13$. Planned comparisons showed that 8-9 year olds (.78) selected the better strategy less often than 10-11 year olds (.86), $F(1,57) = 6.11$, $MSe = 0.79$, $\eta^2_p = .13$, and 12-13 year olds (.86), $F(1,57) = 6.15$, $MSe = 0.79$, $\eta^2_p = .14$. All children also selected the better strategy more often in the memory task (.93) than in the arithmetic task (.74), $F(1,57) = 69.16$, $MSe = 0.79$, $\eta^2_p = .56$. An Age x Task interaction came out significant, $F(2,57) = 4.30$, $MSe = 0.79$, $\eta^2_p = .14$, indicating that 8-9 year olds (.64) had lower rates of better strategy selection than 10-11 year olds (.79), $F(1,57) = 6.51$, $MSe = 1.81$, $\eta^2_p = .13$, and 12-13 year olds (.80), $F(1,57) = 6.77$, $MSe = 1.81$, $\eta^2_p = .16$, in the arithmetic task. No age effects ($F_s < 1$) were found in the memory task.

Better strategy selection latencies. Children were faster at selecting the better strategy as they grow older, $F(2,57) = 3.04$, $MSe = 505399200$, $p = .056$, $\eta^2_p = .10$. Planned comparisons revealed that 8-9 year olds (5978 ms) were slower than 12-13 year olds (4270 ms) to select the better strategy, $F(1,57) = 6.01$, $MSe = 413844500$, $\eta^2_p = .12$. No other effects involving the age factor were found, $F_s < 2.29$. Children were faster to select the better strategy on memory triads (4442 ms) than on arithmetic problems (5938 ms), $F(1,57) = 10.88$, $MSe = 326832900$, $\eta^2_p = .17$. The Age x Task interaction was not significant, $F < 1$.

Better strategy execution times. Children were faster to execute the better strategy in the memory task (5827 ms) than in the arithmetic task (6698 ms), $F(1,57) = 7.43$, $MSe = 161981800$, $\eta^2_p = .12$. No other main or interaction effects reached significance, all $F_s < 1.54$.

Relations between domains. To examine whether performance for the arithmetic task was related to performance for the memory task, we tested whether better strategy selection rates or better strategy selection latencies correlated between the two tasks in each age group. No correlations were significant, all $r_s < .26$, all $p_s > .29$. This means that a child who was good at selecting the better strategy in one domain did not necessarily select the better strategy in the other domain. It also means that a child who was fast at selecting the better strategy in one domain was not

necessarily fast at doing it in the other domain. More generally, these suggest domain specificity of strategy selection and strategy execution.

In sum, these results showed that older children selected the better strategy more often than younger children, but that these age-related differences were significant only in the arithmetic task. All children were also faster to select and execute the better strategy in the memory task than in the arithmetic task. Moreover, measures of rates of and latencies for better strategy selection did not correlate between tasks. This is probably because children's strategy selection accuracy had already reached a peak for the memory task, but still showed improvements for the arithmetic task, suggesting domain-specific strategy selection processes. This hypothesis is strengthened by the lack of covariations between strategy selection times across domains.

Age-related changes in metacognitive processes. We calculated three measures of metacognitive sensitivity for both the arithmetic and the memory tasks: ϕ , γ , and A'_{ROC} . The ϕ coefficient represents the correlation between selection accuracy (better or poorer strategy selection was the objective measure of performance) and metacognitive judgments (Kornell, Son, & Terrace, 2007). The γ coefficient is a non-parametric correlation coefficient that is calculated by taking the difference between concordances (e.g., a high judgment on better strategy selection) and discordances (e.g., a high judgment on poorer strategy selection) and measuring the strength of the association between these cross tabulated data (Nelson, 1984). The A'_{ROC} is a non-parametric measure from signal detection theory which plots the concordances against the discordances (Kornbrot, 2006). Relative to ϕ and γ coefficients, A'_{ROC} has the theoretical advantage of being uninfluenced by the overall bias of a participant to rate his or her confidence as high or low. An ϕ and a γ coefficients of zero or an A'_{ROC} of 0.5 indicate no metacognitive discrimination between better or poorer strategy selections. Interestingly, because these three indexes are non-parametric, they do not depend on strong assumptions about the nature of the underlying distributions. Consequently, they can be computed even when data are not normally distributed (e.g., Fleming et al., 2014).

We first examined whether children were able to make above chance EoS judgments for the two strategy selection tasks. Results of the t tests showed that the three metacognitive coefficients were significantly larger than chance in both the arithmetic and the memory tasks for all age groups (see Table 2).

< Table 2 >

Next, we tested effects of age and task on ϕ , γ , and A'_{ROC} . These three metacognitive coefficients were analyzed with mixed-design ANOVAs, 3 (Age: 8-9-, 10-11, 12-13 year olds) x 2 (Task: arithmetic, memory), with age as the between-participants factor. Metacognitive sensitivity in both the arithmetic and memory tasks increased with age when assessed with the ϕ coefficient, $F(2,57) = 7.46$, $MSe = 2.62$, $\eta^2_p = .21$, the γ coefficient, $F(2,57) = 6.12$, $MSe = 16.83$, $\eta^2_p = .18$, and the A'_{ROC} index, $F(2,57) = 5.82$, $MSe = 0.46$, $\eta^2_p = .17$. Specifically, results of pairwise comparisons consistently showed that 8-9 year olds had lower metacognitive accuracy than 10-11 year olds and 12-13 year olds, and that 10-11 year olds had lower metacognitive accuracy than 12-13 year olds, all $F_s > 5.25$. No main effects of task and no Age x Task interactions were found, all $F_s < 2.85$.

Domain-specificity/-generality of metacognition. To determine whether metacognitive monitoring for strategy selection is domain-general or domain-specific, we first examined relations between metacognitive measures across the arithmetic and memory domains in each age group. Correlational plots for each age group and each metacognitive measure are presented in the Appendix (Figure A1). None of the three metacognitive values significantly correlated across domains in 8-9 year olds, all $r_\phi = .17$, $p = .47$, $r_\gamma = .10$, $p = .68$, $r_{ROC} = .14$, $p = .56$. However, a medium correlation was found between ϕ coefficients in 10-11 year olds, $r = .48$, $p = .03$, and a large correlation was found in 12-13 year olds, $r = .67$, $p = .01$. Similarly, the A'_{ROC} indexes for both the arithmetic and memory tasks correlated in 10-11 year olds, $r = .55$, $p = .01$, and in 12-13 year olds, $r = .83$, $p < .001$. No significant correlations were found between γ coefficients, $r_s < .27$, $p_s > .25$. However, the lack of correlations between γ should be interpreted with caution because of systematic biases in this

measure (Masson & Rotello, 2009). We tested differences between these correlations with *R*-to-*Z* Fisher tests. Correlations between ϕ coefficients were larger in 12-13 year olds than in 8-9 year olds ($r_s = .17$ vs. $.67$, $p = .03$). Correlations between A'_{ROC} indexes were larger in 12-13 year olds than in 8-9 year olds ($r_s = .18$ vs. $.83$, $p = .002$) and in 10-11 year olds ($r_s = .55$ vs. $.83$, $p = .05$). No other differences were found, $ps > .08$.

When examined separately, the three metacognitive measures broadly indicated age-related changes in relations between judgments across domains. To examine whether this pattern held when all measures are considered conjointly, we conducted canonical correlation analyses for each age group to find the maximal correlation between the linear combination of the three metacognitive scores computed for each task (Hair, Anderson, Tatham, & Black, 1998). Results showed no significant relations at age 8-9, $r = .61$, $\chi^2(9) = 8.22$, $p = .51$. However, the two sets of metacognitive indexes tended to correlate at age 10-11, $r = .72$, $\chi^2(9) = 15.54$, $p = .08$, and significantly correlated at age 12-13, $r = .86$, $\chi^2(9) = 23.74$, $p = .004$.

To rule out the possibility that our results were due to the fact that older children make more similar absolute judgments across tasks as compared to young children, we conducted Pearson's correlation analyses between EoS judgments reported for the arithmetic and memory tasks in each age group. Results revealed that EoS judgments for both tasks significantly correlated at all ages, $r = .69$, $p < .001$ at age 8-9, $r = .75$, $p < .001$ at age 10-11, and $r = .60$, $p < .001$ at age 12-13. Moreover, we tested differences between these correlations with *R*-to-*Z* Fisher tests. No significant differences were found, all $ps > .24$. This pattern suggests that the developmental changes observed across domains for the metacognitive indexes were probably not due to age-related differences in children's response bias scores, but to differences in the ability of participants to discriminate between better or poorer strategy selections.

Nevertheless, significant correlations between metacognitive scores for the arithmetic and memory tasks are not sufficient to conclude that metacognitive scores cluster together

independently of domain. To test this more strongly, we used an Exploratory Factorial Analysis (EFA) across the three measures of metacognitive sensitivity for the two strategy selection tasks and for each age group. Six variables were included in these analyses. Two factors accounting for 46% and 45% of the variance emerged with an eigenvalue exceeding 1 (Kaiser's criterion) for 8-9-years-old group (see Table 3). All arithmetic scores loaded highly on Factor 1, whereas all memory scores loaded highly on Factor 2. Two factors explaining 61% and 25% of the variance emerged for 10-11-years-old children. All scores loaded highly in Factor 1, except for the γ coefficient for the memory task. Finally, two factors accounting for 60% and 23% of the variance emerged for 12-13-years-old children. ϕ and A'_{ROC} indexes for both the arithmetic and the memory tasks loaded highly in Factor 1, while the two γ coefficients loaded highly in Factor 2.

< Table 3 >

Overall, the results of these correlational and factorial analyses provide support for the hypothesis that metacognitive abilities shift from domain-specific to domain-general during the course of childhood.

Discussion

Experiment 1 provided information about (a) children's abilities to select and execute the better strategy in arithmetic and in memory, (b) the accuracy with which children predict whether they would select the better strategy, and (c) the developmental course of changes from domain-specific to domain-general metacognition.

Although findings regarding the two strategy selection tasks should be interpreted with cautions as evaluating one's own performance for a task may modify how this task is performed, it is interesting to note that our results replicate improved strategy selection with age. Moreover, this experiment is the first to provide information on the speed with which children select the better strategy. In all previous studies, strategy selection times were not examined independently of strategy execution times, making it impossible to distinguish between these two processes.

Experiment 1 also showed that even 8-9-years-old children are able to make accurate metacognitive judgments during strategy selection in both the arithmetic and memory domains. We found above chance relations between rates of better strategy selection and EoS judgments across age groups, tasks, and multiple metacognitive measures. This indicates that children can introspect on their own strategy choices.

Finally, our results are also the first to show that metacognition possibly shifts from domain-specific to domain-general during childhood, as revealed by age-related differences in relations between metacognitive measures for each type of tasks. Specifically, it appears that this transition occurs between ages of 10 and 13 years. Data suggest that generalization of metacognition should not be viewed as occurring suddenly. Rather, gradual evolution is likely in the metacognitive system, with 10-11 year-old children being in a transition phase. Interestingly, this pattern was observed despite the finding that age-related changes in strategy selection differed in the arithmetic and memory domains (i.e., increased rates of better strategy selection in the arithmetic task, but not in the memory task), resulting in no correlations between measures of better strategy selection for the two tasks. If strategy selection is domain-specific at all ages, changes at the strategy selection level could not account for the developmental trend toward generalization that is observed at the metacognitive level.

Experiment 2

Metacognition is usually evaluated using two main types of judgments: prospective judgments, such as EoS, and retrospective judgments, such as RCJ. Previous studies have established that these two types of judgments are relatively independent from each other, even when they are made within the same cognitive domain (e.g., Kelemen et al., 2000; Pannu & Kaszniak, 2005), suggesting that these judgments likely capture different aspects of metacognition. Consequently, if the developmental trajectory of the generalization of metacognition across domains depends on the type of judgments, these differences should be particularly pronounced between prospective and

retrospective judgments. Conversely, if the pattern of results for prospective judgments is replicated for retrospective judgments, it would further support the hypothesis of a developmental shift from domain-specific to domain-general metacognition.

For this reason, the primary goal of Experiment 2 was to investigate whether the pattern of relations observed between prospective metacognitive judgments for the arithmetic and memory tasks in Experiment 1 could also be found using retrospective judgments. To test this, 8- to 13-years-old children were recruited and asked to estimate on a trial-by-trial basis their level of confidence in a strategy once selected.

Method

Participants. A new sample of 60 typically developing children aged 8-9 (grade 5; $n = 20$; 10 girls; mean age = 8.99 years; $SD = 0.51$), 10-11 (grade 6; $n = 20$; 10 girls; mean age = 10.98 years; $SD = 0.52$), and 12-13 (grade 7; $n = 20$; 9 females; mean age = 12.79 years; $SD = 0.59$) years was recruited. The native language of all children was French, and all children were from a middle- to upper-class socioeconomic status. One additional participant was tested but excluded from the final analyses because he selected the same strategy on all items in the arithmetic task. No group differences were found in levels parental education and in non-verbal intelligence, $F_s < 1$. The sample was recruited from elementary and secondary schools in Belgium.

Stimuli and procedure. Stimuli were the same as in Experiment 1. The procedure was also the same as in Experiment 1, except that we asked children to make RCJ instead of EoS judgments. Each stimulus of the arithmetic and the memory tasks went to three main phases that were presented in the following order: (a) the selection phase, (b) the judgment phase, and (c) the execution phase (see Figure 1).

The selection phase was identical to that in Experiment 1. In Experiment 2, however, this phase was immediately followed by a RCJ assessment during which children were instructed to indicate their level of confidence in the selected strategy. A thermometer procedure was used to

enable children to make their judgments. The position of the cursor on the horizontal thermometer was transformed into a RCJ percentage score (50%, 60%, 70%, 80%, 90%, and 100%). The lowest position on the thermometer indicated that children judged that the strategy was selected randomly. As participants had to select among two available strategies, they had at least a 50% chance to choose the better strategy. The judgment phase was followed by an execution phase that was similar to that in Experiment 1.

Results

We conducted the same analyses as in Experiment 1. Unless otherwise noted, differences are significant to at least $p < .05$. Preliminary analyses indicated no gender, order, or type of pairs' effects on any of the dependent variables. Again, no outliers were found, all $ps > .05$.

Age-related changes in strategic variations. Mean rates of better strategy selections, mean selection latencies, and mean execution times for the arithmetic and memory tasks were analyzed to test age-related and task-related differences in strategy selection and execution. We did not analyze mean rates of better strategy execution because most children made no execution errors. Rates of better strategy selection, mean strategy selection latencies, and mean strategy execution times were analyzed with mixed-design ANOVAs, 3 (Age: 8-9, 10-11, 12-13 year olds) \times 2 (Task: arithmetic, memory), with age as the only between-participants factor (see means in Table 4).

Better strategy selection rates. Rates of better strategy selection increased with children's age, $F(2,57) = 6.95$, $MSe = 1.36$, $\eta^2_p = .20$. Planned comparisons showed that 8-9 year olds (.76) selected the better strategy less often than 10-11 year olds (.83), $F(1,57) = 4.53$, $MSe = 1.16$, $\eta^2_p = .09$, and than 12-13 year olds (.88), $F(1,57) = 13.80$, $MSe = 1.16$, $\eta^2_p = .29$. No differences were found between the two older groups, $F = 2.52$. All children also selected the better strategy more often in the memory task (.91) than in the arithmetic task (.74), $F(1,57) = 52.23$, $MSe = 0.94$, $\eta^2_p = .48$. The significant Age \times Task interaction, $F(2,57) = 4.46$, $MSe = 0.94$, $\eta^2_p = .14$, resulted from age-related

increased rates of better strategy selection in the arithmetic task, $F(2,57) = 7.34$, $MSe = 1.79$, $\eta^2_p = .20$, and no age effects in the memory task, $F = 1.06$.

< Table 4 >

Better strategy selection latencies. Older children were faster to select the better strategy than younger children, $F(2,57) = 15.35$, $MSe = 318536900$, $\eta^2_p = .35$. Planned comparisons showed that 8-9 year olds (8500 ms) were slower to select the better strategy than 10-11 year olds (6472 ms), $F(1,57) = 14.72$, $MSe = 208645600$, $\eta^2_p = .23$, and than 12-13 year olds (5656 ms), $F(1,57) = 28.95$, $MSe = 208645600$, $\eta^2_p = .38$. No significant differences were found between the two older groups, $F = 3.28$. All children were faster to select the better strategy in the memory task (6278 ms) than in the arithmetic task (7476 ms), $F(1,57) = 11.18$, $MSe = 219591800$, $\eta^2_p = .16$. Finally, the Age x Task interaction came out significant, $F(2,57) = 9.88$, $MSe = 219591800$, $\eta^2_p = .26$. This interaction resulted from (a) significant differences in selection latencies between each group, $F_s > 5.35$, in the arithmetic task, and (b) significant differences in latencies between the older group of children and each of the younger groups, $F_s > 4.02$, and no difference between the two youngest group, $F = 0.62$, in the memory task.

Better strategy execution times. Older children were faster to execute the better strategy than young children, $F(2,57) = 7.17$, $MSe = 532931400$, $\eta^2_p = .20$. Planned comparisons indicated that 8-9 year olds (7067 ms) were slower to execute the better strategy than 10-11 year olds (4493 ms), $F(1,57) = 14.17$, $MSe = 318161300$, $\eta^2_p = .29$, and than 12-13 year olds (5541 ms), $F(1,57) = 4.98$, $MSe = 318161300$, $\eta^2_p = .10$. No differences were found between 10-11 year olds and 12-13 year olds, $F = 2.35$. No other main or interaction effects reached significance, all $F_s > 1.02$.

Relations between domains. No correlations between the two types of tasks in better strategy selection rates and in better strategy selection latencies were significant for each age group, all $r_s < .26$, all $p_s > .27$.

In sum, like Experiment 1, Experiment 2 revealed that older children selected the better strategy more often than younger children, and that these age-related differences were only significant in the arithmetic task. Older children were faster to select and execute the better strategy than younger children in both tasks. All children were also faster to select the better strategy during the memory task than during the arithmetic task. Moreover, no correlations in strategy selections were found between the two domains, suggesting domain-specific strategy selection processes.

Age-related changes in metacognitive processes. As in Experiment 1, we computed three measures of metacognitive sensitivity: ϕ , γ , and A'_{ROC} . First, we examined whether the accuracy of children RCJ was statistically greater than chance. The t tests showed that each measure of metacognitive sensitivity was significantly above chance in the arithmetic task for all age groups and in the two older age groups in the memory task (see Table 5).

To assess effects of age and of task, we analyzed children's scores on each of the three metacognitive coefficients with mixed-design ANOVAs, with age as the only between-participants factor. Older children showed a trend toward a higher metacognitive sensitivity than younger children for the ϕ coefficients, $F(2,57) = 2.94$, $MSe = 3.86$, $p = .061$, $\eta^2_p = .09$. Specifically, 8-9 year olds had lower metacognitive sensitivity than 10-11 year olds, $F(1,57) = 5.38$, $MSe = 2.38$, and than 12-13 year olds, $F(1,57) = 3.18$, $MSe = 2.38$. No differences were found between the two older groups, $F = 0.28$. No other main or interaction effects reached significance, all $F_s > 2.24$.

< Table 5 >

Domain-specificity/-generality of metacognition. To examine the developmental trajectory of the domain-specificity of metacognition, we first conducted Pearson's correlation analyses between metacognitive measures across the arithmetic and memory domains for each age group. Correlational plots for each age group and each metacognitive measure are presented in the Appendix (Figure A2). None of the metacognitive values significantly correlated across domains for 8-9-years-old children, $r_\phi = -.17$, $p = .48$, $r_\gamma = -.03$, $p = .87$, $r_{ROC} = -.01$, $p = .94$. Significant correlations

were found between ϕ coefficients, $r = .56, p = .011$, γ coefficients, $r = .45, p = .045$, and A'_{ROC} indexes, $r = .62, p = .004$, for 10-11 year olds. Similarly, ϕ coefficients, $r = .45, p < .001$, γ coefficients, $r = .51, p < .001$, and A'_{ROC} indexes, $r = .40, p = .002$, significantly correlated for 12-13 year olds. We tested differences in these correlations with *R*-to-*Z* Fisher tests. Correlations between ϕ coefficients were smaller for 8-9 year olds than for 10-11 year olds ($r_s = -.17$ vs. $.56, p = .012$) and than for 12-13 year olds ($r_s = -.17$ vs. $.73, p = .001$). Correlations between γ coefficients were larger for 12-13 year olds than for 8-9 year olds ($r_s = -.04$ vs. $.87, p < .001$) and than for 10-11 year olds ($r_s = .45$ vs. $.87, p = .009$). Finally, correlations between A'_{ROC} indexes were smaller for 8-9 year olds than for 10-11 year olds ($r_s = -.02$ vs. $.62, p = .018$) and than for 12-13 year olds ($r_s = -.02$ vs. $.60, p = .022$). No other age differences were found in these correlations, all $ps > .13$.

Next, we conducted canonical correlation analyses for each age group. Results showed no significant relations between measures for 8-9-years-old group, $r = .51, \chi^2(9) = 5.30, p = .81$. The sets of metacognitive measures for the arithmetic and the memory tasks correlated for 10-11-years-old group, $r = .70, \chi^2(9) = 20.01, p = .017$, and 12-13-years-old group, $r = .90, \chi^2(9) = 32.94, p < .001$.

To rule out the possibility that our patterns of results were due to the fact that older children had more stable response bias scores across tasks as compared to young children, we conducted Pearson's correlation analyses between RCJs for both tasks in each age group. Data indicated that absolute RCJs were significantly correlated in each age group, $r = .42, p = .04$ at age 8-9, $r = .40, p = .05$ at age 10-11, and $r = .48, p = .03$ at age 12-13. None of the *R*-to-*Z* Fisher tests conducted to examine differences between these correlations were significant, all $ps > .38$. This suggests that there are no age-related differences in the correlations between RCJs in the arithmetic and in the memory tasks.

Finally, like in Experiment 1, to further investigate whether our six measures of metacognitive sensitivity started to cluster independently of the domain in a specific age group, we conducted EFAs for each age group. Factor loadings are presented in Table 6. Two factors accounting

for 51% and 39% of the variance emerged with an eigenvalue exceeding 1 for 8-9 year olds. All arithmetic scores loaded highly on Factor 1, whereas all memory scores loaded highly on Factor 2. Two factors explaining 65% and 18% of the variance emerged for 10-11 year olds. All scores loaded highly in Factor 1. Finally, only one factor accounting for 77% of the variance emerged with an eigenvalue exceeding 1 for 12-13 year olds, indicating that the metacognitive variables of both the arithmetic and memory domains clustered together.

< Table 6 >

Overall, these findings are consistent with the conclusion that children's metacognitive abilities first segregate by content domain, at least until the age of 8-9 years, but are no more bounded to specific domains by the age of 12-13 years.

Discussion

Experiment 2 replicated the results of Experiment 1, indicating that children are capable of uncertainty monitoring for strategy selection task in two different cognitive domains. Furthermore, correlation analyses showed significant relations between strategy selection accuracy and RCJ for 10-11 year olds and 12-13 year olds, but not for 8-9 year olds, which was confirmed by the results of the canonical correlations and the EFAs. This suggests that change from domain-specific to domain-general metacognition also occurs when children make retrospective metacognitive judgments. As in Experiment 1, this pattern is observed despite the fact that children's strategy selection performance seems to involve domain-specific processes and distinct developmental paths.

The main difference between Experiments 1 and 2 is the lack of age-related differences in metacognitive sensitivity for strategy selection. This is consistent with findings in the developmental literature indicating that the effects of age on metacognitive sensitivity are usually smaller for retrospective judgments than for prospective judgments (Schneider & Lockl, 2008). The fact that two metacognitive judgments with different developmental trajectories show similar change from

domain-specific to domain-general metacognitive mechanisms provides evidence for the robustness of our findings.

Experiment 3

In Experiments 1 and 2, the rates of better strategy selection were higher in the memory task than in the arithmetic task, indicating that these two tasks were not of equal difficulty. Moreover, ceiling effects were revealed for the memory task in both Experiments 1 and 2. As task difficulty has been shown to influence participants' metacognitive judgments (Schraw & Roedel, 1994), this could potentially account for the metacognitive differences observed between age groups in our two experiments. For this reason, the aim of Experiment 3 was to replicate Experiment 2, but this time in reducing differences in tasks difficulty.

Method

Participants. A new sample of 72 typically developing children aged 8-9 (grade 5; $n = 24$; 13 girls; mean age = 9.25 years; $SD = 0.48$), 10-11 (grade 6; $n = 24$; 13 girls; mean age = 11.19 years; $SD = 0.43$), and 12-13 (grade 7; $n = 24$; 16 girls; mean age = 12.79 years; $SD = 0.60$) years was recruited. The native language of all children was French, and all children were from a middle- to upper-class socioeconomic status. No group differences were found in levels parental education and in non-verbal intelligence, $F_s < 1$. The sample was recruited from elementary and middle schools in Belgium.

Stimuli and procedure. Stimuli were the same as in Experiments 1 and 2, except that both the arithmetic and the memory tasks included 32 stimuli instead of 40. The stimuli were selected so as to reduce differences in tasks difficulty. In the arithmetic task, we included the 32 problems to which children responded the most correctly in Experiments 1 and 2. In the memory task, we selected the 32 triads to which children responded the least correctly in the two previous experiments. The procedure was the same as in Experiment 2. Each stimulus of the arithmetic and memory tasks went to three main phases that were presented in the following order: (a) the

selection phase, (b) the judgment phase, and (c) the execution phase (see Figure 1). In the judgment phase, we asked children to make RCJ.

Results

We conducted the same analyses as in Experiments 1 and 2. Unless otherwise noted, differences are significant to at least $p < .05$. Preliminary analyses indicated no gender, order, or type of pairs' effects on any of the dependent variables. Also, no outliers were found, all $ps > .17$

Age-related changes in strategic variations. Mean rates of better strategy selections, mean selection latencies, and mean execution times for the arithmetic and the memory tasks were analyzed to test age-related and task-related differences in strategy selection and execution. We did not analyze mean rates of better strategy execution because most children made no execution errors. Rates of better strategy selection, mean strategy selection latencies, and mean strategy execution times were analyzed with mixed-design ANOVAs, 3 (Age: 8-9, 10-11, 12-13 year olds) \times 2 (Task: arithmetic, memory), with age as the only between-participants factor (see means in Table 7).

Better strategy selection rates. Rates of better strategy selection increased with children's age, $F(2,69) = 6.72$, $MSe = 0.29$, $\eta^2_p = .16$. Planned comparisons showed that 8-9 year olds (.84) selected the better strategy less often than 12-13 year olds (.89), $F(1,69) = 12.98$, $MSe = 0.29$, $\eta^2_p = .26$. No other differences were found between groups, $F_s < 2.44$, $ps > .09$. No other effects reached significance, all $F_s < 1$.

< Table 7 >

Better strategy selection latencies. Older children were faster at selecting the better strategy than younger children, $F(2,69) = 5.82$, $MSe = 270900300$, $\eta^2_p = .14$. Planned comparisons showed that 8-9 year olds (6346 ms) were slower at selecting the better strategy than 10-11 year olds (5547 ms), $F(1,69) = 3.91$, $MSe = 270900278$, $\eta^2_p = .08$, and than 12-13 year olds (4972 ms), $F(1,69) = 11.53$, $MSe = 270900278$, $\eta^2_p = .20$. No significant differences were found between the two older groups, $F =$

2.02. All children were faster at selecting the better strategy for the memory task (4701 ms) than for the arithmetic task (6543 ms), $F(1,69) = 37.02$, $MSe = 227617800$, $\eta^2_p = .35$. The Age x Task interaction was not significant, $F < 1$.

Better strategy execution times. Older children were faster at executing the better strategy than young children, $F(2,69) = 10.41$, $MSe = 408859900$, $\eta^2_p = .23$. Planned comparisons indicated that 8-9 year olds (6742 ms) were slower at executing the better strategy than 10-11 year olds (5269 ms), $F(1,69) = 8.78$, $MSe = 408859878$, $\eta^2_p = .14$, and than 12-13 year olds (4512 ms), $F(1,69) = 20.13$, $MSe = 408859878$, $\eta^2_p = .33$. No differences were found between 10-11 year olds and 12-13 year olds, $F = 2.32$, $p = .13$. No other main or interaction effects reached significance, all $F_s < 1$.

Relations between strategic domains. No correlations between better strategy selection rates and better strategy selection latencies for the two types of tasks for each age group were significant, all $r_s < .26$, all $p_s > .21$.

In sum, Experiment 3 revealed that older children select the better strategy more often than younger children. The lack of significant Age x Task interaction suggests that our manipulation to reduce differences in tasks difficulty was successful. As in Experiments 1 and 2, older children were faster to select and execute the better strategy than younger children in both tasks. All children were also faster to select the better strategy during the memory task than during the arithmetic task. Although differences in task difficulty were reduced in the present experiment, no correlations in strategy selections were found between the two domains, confirming domain-specific strategy selection processes.

Age-related changes in metacognitive processes. We computed three measures of metacognitive sensitivity: ϕ , γ , and A'_{ROC} . First, we examined whether the accuracy of children RCJ was statistically greater than chance. The t tests showed that each measure of metacognitive sensitivity was significantly above chance in both the arithmetic and the memory tasks for all age groups (see Table 8).

To assess age and task effects, we analyzed children's scores on each of the three metacognitive coefficients with mixed-design ANOVAs, with age as the only between-participants factor. Older children showed a higher metacognitive sensitivity than younger children for A'_{ROC} coefficients, $F(2,69) = 3.15$, $MSe = 1.95$, $\eta^2_p = .08$, and a trend toward a higher metacognitive sensitivity for the ϕ coefficients, $F(2,69) = 2.81$, $MSe = 5.60$, $p = .066$, $\eta^2_p = .08$. Specifically, 8-9 year olds had lower metacognitive sensitivity than 12-13 year olds, for both the A'_{ROC} , $F(1,69) = 6.29$, $MSe = 1.94$, and the ϕ , $F(1,69) = 5.02$, $MSe = 5.61$. No other differences between groups were found, $F_s < 3.21$. No other main or interaction effects reached significance, all $F_s < 1.98$.

< Table 8 >

Domain-specificity/-generality of metacognition. To examine the developmental trajectory of the domain-specificity of metacognition, we first conducted Pearson's correlation analyses between metacognitive measures across the arithmetic and memory domains for each age group. Correlational plots for each age group and each metacognitive measure are presented in the Appendix (Figure A3). None of the metacognitive values significantly correlated across domains in 8-9-years-old children, $r_\phi = .11$, $p = .62$, $r_\gamma = .16$, $p = .45$, $r_{ROC} = .26$, $p = .21$. However, significant correlations were found between ϕ coefficients, $r = .50$, $p = .013$, γ coefficients, $r = .46$, $p = .025$, and A'_{ROC} indexes, $r = .64$, $p = .001$, in 10-11 year olds. Similarly, ϕ coefficients, $r = .81$, $p < .001$, γ coefficients, $r = .63$, $p = .001$, and A'_{ROC} indexes, $r = .78$, $p < .001$, significantly correlated in 12-13 year olds. We tested differences between these correlations with R -to- Z Fisher tests. Correlations between ϕ coefficients were smaller for 8-9 year olds than for 12-13 year olds ($r_s = .11$ vs. $.81$, $p = .002$). Correlations between γ coefficients were larger in 12-13 year olds than in 8-9 year olds ($r_s = .16$ vs. $.63$, $p = .047$). Finally, correlations between A'_{ROC} indexes were smaller in 8-9 year olds than in 12-13 year olds ($r_s = .26$ vs. $.78$, $p = .015$). No other age differences were found in these correlations, all $p_s > .11$.

Next, we conducted canonical correlation analyses for each age group. Results showed no significant relations between measures in 8-9 years olds, $r = .53$, $\chi^2(9) = 9.11$, $p = .43$, but the sets of metacognitive measures for the arithmetic and memory tasks correlated in 10-11 years olds, $r = .85$, $\chi^2(9) = 31.92$, $p < .001$, and in 12-13 years olds, $r = .86$, $\chi^2(9) = 31.86$, $p < .001$.

We also conducted Pearson's correlation analyses between RCJs for both tasks in each age group. Results indicated that RCJs of both tasks were significantly correlated in each age group, $r = .42$, $p = .02$ at age 8-9, $r = .34$, $p = .04$ at age 10-11, and $r = .41$, $p = .02$ at age 12-13. None of the R-to-Z Fisher tests conducted to examine differences between these correlations were significant, all $ps > .38$. Overall, these findings suggest that the developmental changes observed across domains in the metacognitive indexes were not due to age-related differences in children's response bias scores, but to differences in their abilities to discriminate between better or poorer strategy selections.

To further investigate whether our six measures of metacognitive sensitivity started to cluster independently of the domain in a specific age group, we conducted EFAs for each age group. (see factor loadings in Table 9). Two factors accounting for 53% and 37% of the variance emerged with an eigenvalue exceeding 1 for 8-9 year olds. All arithmetic scores loaded highly on Factor 1, whereas all memory scores loaded highly on Factor 2. Two factors explaining 61% and 20% of the variance emerged for 10-11 year olds. All scores loaded highly on Factor 1. Finally, only one factor accounting for 80% of the variance emerged with an eigenvalue exceeding 1 for 12-13 year olds, indicating that the metacognitive variables of both the arithmetic and the memory domains clustered together.

Finally, to ensure that the nonsignificant correlation in the youngest age group was not due to a lack of statistical power, we combined data from Experiments 2 and 3 and conducted Pearson's correlation analyses between our different metacognitive scores. When the influence of strategy selection rates (which differed in these two experiments) was taken into account, none of the metacognitive values significantly correlated across domains in 8-9-years-old children, $r_\phi = .12$, $p =$

.46, $r_Y = .07$, $p = .64$, $r_{ROC} = .17$, $p = .26$. Moreover, the correlations were still significant for all metacognitive indexes in the older two groups, all $r_s > .59$, all $p_s < .005$. We also conducted regression analyses on this larger sample in order to determine whether the relations between our metacognitive scores across domains interact with children's age (in years). Results confirmed that the relations between our three metacognitive measures for the arithmetic and the memory tasks increased with age, $\beta_\phi = 2.78$, $p < 0.01$, $\beta_Y = 2.34$, $p < .001$, $\beta_{ROC} = 2.83$, $p < .001$.

< Table 9 >

Discussion

Experiment 3 replicated the results of Experiments 1 and 2, suggesting that children are capable of uncertainty monitoring for strategy selection tasks in two different domains. Our findings also confirm that children's metacognitive abilities first segregate by content domain, at least before the age of 10-11 years, but are no more bounded to domain by the age of 12-13 years. Importantly, this pattern was observed while no differences were found in the rates of better strategy selection between the arithmetic and memory tasks. Combined with the results of Experiments 1 and 2, Experiment 3 provides evidence that age-related differences observed in metacognitive sensitivity is likely not due to differences in task difficulty.

General Discussion

Adult metacognition is generally considered as involving domain-general processes that are not bounded to a particular cognitive domain (e.g., Schraw et al., 1995; Song et al., 2011; Veenman et al., 1997). Conversely, studies carried out in children seem to show that metacognition is domain-specific in the early stage of development (e.g., Vo et al., 2014). These diverging results suggest that a development from domain-specific to domain-general occurs in metacognitive abilities between childhood and adulthood. Up until now, however, the exact developmental course of this transition was still unexplored. The present study contributed to this issue by examining the relations between different measures of metacognitive sensitivity in an arithmetic and a memory strategy selection

tasks. Moreover, we also tested how accurate children were to evaluate the success of strategy selection processes. The present findings have important implications to further our understanding of age-related changes in metacognition as it is involved in strategy selection. We next discuss these implications.

Domain-General or Domain-Specific Metacognitive Processes?

The results of Experiments 1—3 consistently indicated that a gradual shift toward domain-general metacognition occurs in children aged between 8 and 13, providing first evidence supporting the hypothesis that metacognition is first domain-specific, and then generalizes across domains as children mature (Schraw et al., 1995; Veenman & Spaans, 2005). These findings are important because they provide key information to improve our understanding of the architecture of metacognition.

The popular dual-process framework of metacognition (e.g., Koriat, 2007; Koriat & Ackerman, 2010; Koriat, Nussinson, Bless, & Shaked, 2008; Stanovich & West, 2000; Thompson, Prowse Turner, & Pennycook, 2011) could provide an interesting framework for interpreting our results. According to this model, two mechanisms come into play when people have to distinguish what they know from what they do not know. On the one hand, metacognitive judgments can be experience-based. This is based on fast and automatic inferences made from a variety of cues (e.g., degree of perceptual detail, processing fluency) that are heuristically used to guide decisions. As experience-based judgments rest on cues that reside from the immediate feedback from the task; they are task-dependent and, thus, probably difficult to generalize across domains. On the other hand, metacognitive judgments can also be information-based. These include conscious and deliberate inferences, in which various pieces of information retrieved from memory are consulted and weighted in order to reach an educated judgment (Koriat, 2007). As information-based processes are conscious and effortful, they are probably more likely to be generalized to other domains than experience-based processes (Pasquali, Timmermans, & Cleeremans, 2010).

Within this framework, the finding that metacognition is domain-specific under the age of 10 years could suggest that young children preferentially rely on automatic inferences when making judgments. This assumption is consistent with the results of recent studies conducted in the memory field, indicating that some mnemonic cues are already used heuristically to guide metacognitive decisions as early as age 4 (see Geurten & Willems, 2016, for an overview). With age, however, effortful cognitive abilities (see Best & Miller, 2011, for a review) and explicit metacognitive knowledge (Geurten, Catale, & Meulemans, 2016) improve. This may enable children to rely more often on conscious and deliberate information-based processes based on general knowledge structure when judging their performance, possibly explaining why metacognition shifts from domain-specific to domain-general during late childhood.

Interestingly, the finding that metacognition is domain-specific before being domain-general could also explain why, although some imaging studies reveal that inter-domain measures of metacognitive sensitivity share some neural substrates (e.g., Allen et al., 2016), others indicate that metacognition is sustained by distinct cortical networks (e.g., Baird et al., 2013). It could also explain why adult patients with brain lesions can show domain-specific impairments of metacognition (Fleming, Ryu, Golfinos, & Blackmon, 2014). Indeed, if metacognitive skills first develop within domain before generalizing across domains, it is likely that these skills involved distinct neuro-anatomic regions in addition to common ones (as it is the case for executive functions, Collette et al., 2005). Moreover, according to the dual-processes framework, experience-based (probably more domain-specific) and information-based (probably more domain-general) processes can be activated in parallel during the same task. The predominance of one of these processes over the other depends on the context, the task, and the available cognitive resources (Koriat et al., 2008). In other words, it is possible that metacognition remains characterized by both specificity and generality of processes, even in adulthood. Domain-specific aspects could thus be differentially affected by neurological insult (Fleming et al., 2014). This hypothesis, however, has to be further examined, just as our results have to be confirmed by examining intra-individual changes in domain-general metacognition over

time. Indeed, the interpretation of our data within the dual-process framework is still mostly speculative since our study was not designed to test this model.

Consistent with previous findings, the sensitivity of prospective judgments greatly increased with age while improvements in retrospective judgments were less substantial, probably explaining why only one or two of our three metacognitive measures were able to capture age-related improvements in RCJ sensitivity in Experiments 2 (phi coefficient) and 3 (phi and A'ROC coefficient). The higher variability of the gamma coefficient probably explains why this index was not able to discriminate between our three age groups in these two experiments. It is interesting to note that differences in the developmental trajectory of prospective and retrospective judgments do not seem to affect the generalization of metacognitive processes across domains. Domain-general metacognition seems to appear approximately at the same age for both types of judgments. This suggests that the development of domain-general metacognition does not depend on changes in the absolute level of metacognitive sensitivity, but rather on changes in processes underlying how metacognitive judgments are made.

Metacognition and Strategy Selection

The present results replicate previous findings on strategic behaviors and age-related improvements in how children select and execute strategies for both the arithmetic and the memory tasks. They also document new findings that shed important light on how participants evaluate their strategy selection. Specifically, our results examining the sensitivity of children's metacognitive judgments indicate that children from 8 to 13 years are able to accurately estimate whether they select the better strategy on a given item in both the arithmetic and the memory domains. Furthermore, metacognitive sensitivity for strategy selection seems to increase with age.

From a theoretical perspective, the finding that metacognitive sensitivity for strategy selection tasks improves with age in both the arithmetic and the memory domains provides a first and crucial prerequisite to validate the hypothesis that metacognitive skills can account for age-

related differences in children's strategy selection and execution (e.g., Lemaire & Lecacheur, 2011). Indeed, according to classical models of metacognition (Nelson & Narens, 1990), making accurate evaluations of the success of cognitive processes is supposed to increase the likelihood that participants implement effective regulatory behaviors. Consistent with this view, in the arithmetic domain, two of the computational models of strategies (RCCL and SCADS*) assume that strategy choices involve metacognitive mechanisms. In these models, the metacognitive system enables participants to evaluate strategies once selected and to interrupt strategy mid-execution to switch for a better strategy (RCCL) or to discover new legitimate strategies (SCADS*). Although future studies should, of course, be conducted to experimentally test these proposals – e.g., by examining whether children use the results of their metacognitive evaluation to regulate their strategic behaviors – our findings provide a first important step toward the corroboration of these theoretical postulates.

Limitations and Future Directions

The present study raises a number of interesting issues that some future studies may fruitfully address. First, our study examined whether children's ability to *monitor* their cognitive performance shifted from domain-specific to domain-general. However, we did not explore whether participants' ability to *regulate* their performance followed the same developmental path. As the developmental course of metacognitive monitoring and metacognitive control differs in children (see Schneider & Lockl, 2008), it is possible that domain-general metacognition does not emerge at the same time for these two metacognitive components.

Also, although our findings provide crucial information about how metacognition develops throughout childhood, they remain cross-sectional in nature. Yet, only within-individual data collected over time could help to decide whether age-related differences in the relations between metacognitive measures across domains are due to transition from domain-specific to domain-general abilities or to the emergence of a domain-general metacognition independent from domain-

specific metacognitive processes. Another important outstanding issue concerns the mechanisms that underline this developmental path. We assume here that the emergence of information-based metacognition may account for age-related differences observed in relations between metacognitive measures across domains, but this hypothesis remains to be formally tested. Finally, the number of participants recruited in our first two experiments was rather small. In this context, it is possible that our studies were not powerful enough to reveal relations between arithmetic and memory measures of metacognition in young children. Although our third experiment had more power and showed similar results, we cannot totally rule out the hypothesis that there is an embryonic domain-general metacognition in young children that increases with age.

Despite these limitations, the results of the present study seem to indicate that metacognition is no more bounded by task content and domain knowledge after the age of 10. We also found that the metacognitive sensitivity for strategy selection improves with age in both the arithmetic and memory domains. These findings suggest that, at around 10-11 years (or later), a domain-general metacognition begins to operate. This is particularly important for children who suffer from learning disabilities in a specific cognitive sphere (e.g., dyscalculia, dyslexia) because it means that training them to make accurate metacognitive judgments in one domain could potentially improve their metacognitive sensitivity in other domains, including the impaired one. This is an interesting prediction that future studies can test directly by assessing children with cognitive impairments in one or several domains.

Acknowledgments

This work was supported by the Agence Nationale de la Recherche under Grant # BLAN-1912-01 to PL and by a Grant from the Marie-Curie CoFund Program to MG. We have no conflict of interest to declare.

Reference

- Allen, M., Glen, J. C., Mullensiefen, D., Schwarzkopf, D. S., Callaghan, M. F., & Rees, G. (2016). Metacognitive ability predicts hippocampal and prefrontal microstructure. *bioRxiv*. doi:10.1101/046359
- Anderson, J. R., Betts, S., Ferris, J. L., & Fincham, J. M. (2011). Cognitive and metacognitive activity in mathematical problem solving: prefrontal and parietal patterns. *Cognitive, Affective, & Behavioral Neuroscience*, 11, 52–67. doi:10.3758/s13415-010-0011-0
- Ardiale, E., & Lemaire, P. (2012). Within-item strategy switching: An age comparative study in adults. *Psychology and Aging*, 27, 1138–1151. doi:10.1037/a0027772
- Ardiale, E., & Lemaire, P. (2013). Effects of execution duration on within-item strategy switching in young and older adults. *Journal of Cognitive Psychology*, 25, 464–472. doi:10.1080/20445911.2013.789854
- Baird, B., Smallwood, J., Gorgolewski, K. J., & Margulies, D. S. (2013). Medial and lateral networks in anterior prefrontal cortex support metacognitive ability for memory and perception. *The Journal of Neuroscience*, 33, 16657–16665. doi:10.1523/JNEUROSCI.0786-13.2013
- Bjorklund, D. F., Dukes, C., & Brown, R. D. (2009). The development of memory strategies. In M. L. Courage & N. Cowan (Eds.), *The development of memory in infancy and childhood (2nd ed.)* (pp. 145-175). New York: Psychology Press.
- Chua, E. F., Schacter, D. L., & Sperling, R. A. (2008). Neural correlates of metamemory: A comparison of feeling-of-knowing and retrospective confidence judgments. *Journal of Cognitive Neuroscience*, 21, 1751–1765. doi:10.1162/jocn.2009.21123
- Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping*, 25, 409–423. doi:10.1002/hbm.20118

- DeMarie, D., Miller, P. H., Ferron, J., & Cunningham, W. R. (2004). Path analysis tests of theoretical models of children's memory performance. *Journal of Cognition and Development, 5*, 461–492. doi:10.1207/s15327647jcd0504_4
- Desrochers, A., & Bergeron, M. (2000). Value of subjective frequency and imagery for a sample of 1,916 French language nouns. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie experimentale, 54*, 274–325. doi:10.1037/h0087347
- Dunlosky, J., & Metcalfe, J. (2009). *Metacognition*. Thousand Oaks, CA: Sage Publications, Inc.
- Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Frontiers in human neuroscience, 8*. doi:10.3389/fnhum.2014.00443
- Fleming, S. M., Ryu, J., Golfinos, J. G., & Blackmon, K. E. (2014). Domain-specific impairment in metacognitive accuracy following anterior prefrontal lesions. *Brain, 137*, 2811–2822. doi:10.1093/brain/awu221
- Galvin, S. J., Podd, J. V., Drga, V., & Whitmore, J. (2003). Type 2 tasks in the theory of signal detectability: Discrimination between correct and incorrect decisions. *Psychonomic Bulletin & Review, 10*, 843–876. doi:10.3758/bf03196546
- Gardelle, V.d., & Mamassian, P. (2014). Does Confidence Use a Common Currency Across Two Visual Tasks? *Psychological Science, 25*, 1286–1288. doi:10.1177/0956797614528956
- Geurten, M., Catale, C., & Meulemans, T. (2016). Involvement of executive functions in children's metamemory. *Applied Cognitive Psychology, 30*, 70–80. doi:10.1002/acp.3168
- Geurten, M., Lejeune, C., & Meulemans, T. (2016). Time's up! Involvement of metamemory knowledge, executive functions, and time monitoring in children's prospective memory performance. *Child Neuropsychology, 22*, 443–457. doi:10.1080/09297049.2014.998642
- Geurten, M., & Meulemans, T. (2016). The effect of feedback on children's metacognitive judgments: a heuristic account. *Journal of Cognitive Psychology*. doi:10.1080/20445911.2016.1229669

- Geurten, M., & Willems, S. (2016). Metacognition in early childhood: Fertile ground to understand memory development? *Child Development Perspectives*, 10, 263–268.
doi:10.1111/cdep.12201
- Geurten, M., Willems, S., & Meulemans, T. (2015). Beyond the experience: Detection of metamemorial regularities. *Consciousness and Cognition*, 33, 16–23.
doi:10.1016/j.concog.2014.11.009
- Ghatala, E. S. (1986). Strategy–monitoring training enables young learners to select effective strategies. *Educational Psychologist*, 21, 43–54. doi:10.1080/00461520.1986.9653023
- Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1998). *Multivariate data analysis*. New York, NY: Prentice Hall International.
- Kadosh, R. C., & Dowker, A. (2015). *The Oxford Handbook of Numerical Cognition*, New York, NY: Oxford University Press.
- Kelemen, W., Frost, P., & Weaver, C. (2000). Individual differences in metacognition: Evidence against a general metacognitive ability. *Memory & Cognition*, 28, 92–107. doi:10.3758/BF03211579
- Koriat, A. (2007). Metacognition and consciousness. In P. D. Zelazo, M. Moscovitch, & E. Thompson (Eds.), *The Cambridge handbook of consciousness* (pp. 289–325). Cambridge, UK: Cambridge University Press.
- Koriat, A., & Ackerman, R. (2010). Choice latency as a cue for children’s subjective confidence in the correctness of their answers. *Developmental Science*, 13, 441–453. doi:10.1111/j.1467–7687.2009.00907.x
- Koriat, A., Nussinson, R., Bless, H., & Shaked, N. (2008). Information–based and experience–based metacognitive judgments: Evidence from subjective confidence. In J. Dunlosky & R. A. Bjork (Eds.), *Handbook of metamemory and memory* (pp. 117–135). New York, NY: Psychology Press.

- Koriat, A., & Shitzer–Reichert, R. (2002). Metacognitive judgments and their accuracy. In P. Chambres, M. Izaute, & P.-J. Marescaux (Eds.), *Metacognition: Processes, Function, and Use* (pp. 1–17), Norwell, MA: Kluwer Academic Publishers.
- Kornbrot, D. E. (2006). Signal detection theory, the approach of choice: Model-based and distribution-free measures and evaluation. *Perception & Psychophysics*, 68, 393–414.
doi:10.3758/bf03193685
- Kornell, N., Son, L. K., & Terrace, H. S. (2007). Transfer of metacognitive skills and hint seeking in monkeys. *Psychological Science*, 18, 64–71. doi:10.1111/j.1467-9280.2007.01850.x
- Kuhn, D. (2000). Metacognitive development. *Current Directions in Psychological Science*, 9, 178–181.
doi:10.1111/1467-8721.00088
- Lachaud, C. M. (2007). CHACQFAM: une base de données renseignant l'âge d'acquisition estimé et la familiarité pour 1225 mots monosyllabiques et bisyllabiques du Français. *L'année psychologique*, 107, 39–63.
- LeFevre, J.-A., Greenham, S. L., & Waheed, N. (1993). The Development of Procedural and Conceptual Knowledge in Computational Estimation. *Cognition and Instruction*, 11, 95–132.
doi:10.1207/s1532690xci1102_1
- Lemaire, P. (2016). *Cognitive aging: The role of strategies*. London: Routledge.
- Lemaire, P., & Brun, F. (2014). Effects of strategy sequences and response–stimulus intervals on children's strategy selection and strategy execution: A study in computational estimation. *Psychological Research*, 78, 506–519. doi:10.1007/s00426-013-0501-0
- Lemaire, P., & Brun, F. (2016). Age-related differences in children's strategy repetition: A study in arithmetic. *Journal of Experimental Child Psychology*, 150, 227–240.
doi:10.1016/j.jecp.2016.05.014
- Lemaire, P., & Callies, S. (2009). Children's strategies in complex arithmetic. *Journal of Experimental Child Psychology*, 103, 49–65. doi:10.1016/j.jecp.2008.09.007

- Lemaire, P., & Lecacheur, M. (2011). Age-related changes in children's executive functions and strategy selection: A study in computational estimation. *Cognitive Development, 26*, 282–294. doi:10.1016/j.cogdev.2011.01.002
- Lemaire, P., Lecacheur, M., & Farioli, F. (2000). Children's strategy use in computational estimation. *Canadian Journal of Experimental Psychology, 54*, 141–148. doi:10.1037/h0087336
- Lovett, M. C., & Anderson, J. R. (1996). History of success and current context in problem solving: Combined influences on operator selection. *Cognitive Psychology, 31*, 168–217. doi:10.1006/cogp.1996.0016
- Lovett, M. C., & Schunn, C. D. (1999). Task representations, strategy variability, and base-rate neglect. *Journal of Experimental Psychology: General, 128*, 107–130. doi:10.1037/0096-3445.128.2.107
- Lyons, K. E., & Ghetti, S. (2010). Metacognitive development in early childhood: New questions about old assumptions. In A. Efklides & P. Misailidi (Eds.), *Trends and Prospects in Metacognition Research* (pp. 259–278), New York, NY: Springer US.
- Masson, M. E. J., & Rotello, C. M. (2009). Sources of bias in the Goodman–Kruskal gamma coefficient measure of association: Implications for studies of metacognitive processes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 509–527. doi:10.1037/a0014876
- McCurdy, L. Y., Maniscalco, B., Metcalfe, J., Liu, K. Y., de Lange, F. P., & Lau, H. (2013). Anatomical coupling between distinct metacognitive systems for memory and visual perception. *The Journal of Neuroscience, 33*, 1897–1906. doi:10.1523/JNEUROSCI.1890-12.2013
- Metcalfe, A. W. S., & Campbell, J. I. D. (2011). Adults' strategies for simple addition and multiplication: Verbal self-reports and the operand recognition paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 661–672. doi:10.1037/a0022218

- Neches, R. (1987). Learning through incremental refinement of procedures. In D. Klahr, P. Langley, & R. Neches (Eds.), *Production system models of learning and development* (pp. 163–219). Cambridge, MA: The MIT Press.
- Nelson, T. O. (1984). A comparison of current measures of the accuracy of feeling-of-knowing predictions. *Psychological Bulletin*, 95, 109–133. doi:10.1037/0033-2909.95.1.109
- Nelson, T. O., & Narens, L. (1990). Metamemory: a theoretical framework and new findings. *The Psychology of learning and motivation*, 26, 125–141.
- Pannu, J. K., & Kaszniak, A. W. (2005). Metamemory experiments in neurological populations: A review. *Neuropsychology Review*, 15, 105–130. doi:10.1007/s11065-005-7091-6
- Pasquali, A., Timmermans, B., & Cleeremans, A. (2010). Know thyself: Metacognitive networks and measures of consciousness. *Cognition*, 117, 182–190. doi:10.1016/j.cognition.2010.08.010
- Radeau, M., Mousty, P., & Content, A. (1990). Brulex. Une base de données lexicales informatisée pour le français écrit et parlé. *L'année psychologique*, 90, 551–566.
- Rieskamp, J., & Otto, P. E. (2006). SSL: A theory of how people learn to select strategies. *Journal of Experimental Psychology: General*, 135, 207–236. doi:10.1037/0096-3445.135.2.207
- Schneider, W., & Lockl, K. (2008). Procedural metacognition in children: evidence for developmental trends. In J. D. R. A. Bjork (Ed.), *Handbook of metamemory and memory* (pp. 391–409). New York, NY: Psychology Press.
- Schneider, W., & Löffler, E. (2016). The development of metacognitive knowledge in children and adolescents. In J. Dunlosky & S. K. Tauber (Eds.), *The Oxford Handbook of Metamemory* (pp. 491–518). New York, NY: Oxford University Press.
- Schraw, G., Dunkle, M. E., Bendixen, L. D., & Roedel, T. D. (1995). Does a general monitoring skill exist? *Journal of Educational Psychology*, 87, 433–444. doi:10.1037/0022-0663.87.3.433
- Schraw, G., & Nietfeld, J. (1998). A further test of the general monitoring skill hypothesis. *Journal of Educational Psychology*, 90, 236–248. doi:10.1037/0022-0663.90.2.236

- Shimamura, A. P. (2000). Toward a cognitive neuroscience of metacognition. *Consciousness and Cognition*, 9, 313–323. doi:10.1006/ccog.2000.0450
- Siedlecka, M., Paulewicz, B., & Wierzchoń, M. (2016). But I was so sure! Metacognitive judgments are less accurate given prospectively than retrospectively. *Frontiers in Psychology*, 7, 218. doi:10.3389/fpsyg.2016.00218
- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*, New York, NY: Oxford University Press.
- Siegler, R. S. (2007). Cognitive variability. *Developmental Science*, 10, 104–109. doi:10.1111/j.1467–7687.2007.00571.x
- Siegler, R. S., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. *Advances in child development and behaviour*, 33, 1–44.
- Siegler, R. S., & Crowley, K. (1994). Constraints on learning in nonprivileged domains. *Cognitive Psychology*, 27, 194–226. doi:10.1006/cogp.1994.1016
- Siegler, R. S., & Shipley, C. (1995). Variation, selection, and cognitive change. In T. J. S. G. S. Halford (Ed.), *Developing cognitive competence: New approaches to process modeling* (pp. 31–76). Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.
- Son, L. K. (2005). Metacognitive Control: Children's Short–Term Versus Long–Term Study Strategies. *The Journal of General Psychology*, 132, 347–364. doi:10.3200/GENP.132.4.347–364
- Song, C., Kanai, R., Fleming, S. M., Weil, R. S., Schwarzkopf, D. S., & Rees, G. (2011). Relating inter–individual differences in metacognitive performance on different perceptual tasks. *Consciousness and Cognition*, 20, 1787–1792. doi:10.1016/j.concog.2010.12.011
- Stanovich, K. E., & West, R. F. (2000). Individual differences in reasoning: Implications for the rationality debate? *Behavioral and Brain Sciences*, 23, 645–665. doi:10.1017/S0140525X00003435

- Thevenot, C., Fanget, M., & Fayol, M. (2007). Retrieval or nonretrieval strategies in mental arithmetic? An operand recognition paradigm. *Memory & Cognition*, 35, 1344–1352.
doi:10.3758/bf03193606
- Thompson, V. A., Prowse Turner, J. A., & Pennycook, G. (2011). Intuition, reason, and metacognition. *Cognitive Psychology*, 63, 107–140. doi:10.1016/j.cogpsych.2011.06.001
- Veenman, M. V., Elshout, J. J., & Meijer, J. (1997). The generality vs domain–specificity of metacognitive skills in novice learning across domains. *Learning and Instruction*, 7, 187–209.
doi:10.1016/S0959–4752(96)00025–4
- Veenman, M. V., Prins, F. J., & Verheij, J. (2003). Learning styles: Self–reports versus thinking–aloud measures. *British Journal of Educational Psychology*, 73, 357–372.
doi:10.1348/000709903322275885
- Veenman, M. V., & Spaans, M. A. (2005). Relation between intellectual and metacognitive skills: Age and task differences. *Learning and Individual Differences*, 15, 159–176.
doi:10.1016/j.lindif.2004.12.001
- Vo, V. A., Li, R., Kornell, N., Pouget, A., & Cantlon, J. F. (2014). Young children bet on their numerical skills: Metacognition in the numerical domain. *Psychological Science*, 25, 1712–1721.
doi:10.1177/0956797614538458
- Wechsler, D. (2005). *Wechsler Intelligence Scale for Children: WISC–IV*: Les Editions du Centre de Psychologie Appliquée.

Table 1

Mean Better Strategy Selection Rates, Mean Selection Times (in ms), and Mean Execution Times (in ms) in Each Age Group for the Arithmetic and the Memory Tasks, in Experiment 1.

	8-9 year olds	10-11 year olds	12-13 year olds	Means
<i>Arithmetic</i>				
Better strategy selection rates	0.64 (.04)	0.79 (.04)	0.80 (.03)	0.74 (.03)
Better strategy selection times	6349 (708)	6127 (430)	5338 (470)	5938 (413)
Better strategy execution times	7243 (474)	6066 (414)	6784 (463)	6698 (264)
<i>Memory</i>				
Better strategy selection rates	0.91 (.01)	0.93 (.01)	0.92 (.01)	0.92 (.01)
Better strategy selection times	5606 (672)	4520 (485)	3202 (250)	4442 (318)
Better strategy execution times	5942 (649)	5103 (553)	6438 (660)	5828 (369)

Note. Standard errors are in parentheses.

Table 2

Means and Tests of Metacognitive Sensitivity for the Three Age Groups and the Two Strategy Selection Tasks, in Experiment 1

	ϕ		γ		A'_{ROC}	
	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>
<i>Arithmetic</i>						
8-9 year olds	.10 (.03)	2.87*	.31 (.09)	3.55*	.55 (.02)	2.58*
10-11 year olds	.18 (.04)	3.92**	.60 (.12)	4.28**	.55 (.02)	3.47*
12-13 year olds	.32 (.03)	8.57**	.71 (.06)	11.87**	.64 (.02)	6.73**
All	.21 (.02)	8.77**	.50 (.06)	8.78**	.59 (.01)	7.72**
<i>Memory</i>						
8-9 year olds	.16 (.05)	2.64*	.37 (.14)	2.12*	.56 (.02)	3.13*
10-11 year olds	.20 (.06)	5.58**	.47 (.17)	3.92**	.58 (.02)	5.16**
12-13 year olds	.31 (.02)	14.30**	.90 (.02)	37.26**	.60 (.01)	10.48**
All	.22 (.03)	7.93**	.62 (.08)	7.91**	.57 (.01)	7.84**

Note. *t* tests are two-tailed comparisons against chance: i.e., 0 for ϕ and γ ; 0.5 for Area under the Receiver-Operating-Characteristic (ROC) curve (A'_{ROC}). Standard errors are in parentheses.

* $p < .05$; ** $p < .001$

Table 3

Loadings of each Metacognitive Measures on the two Strategy Selection Tasks for Each Age Group, in Experiment 1

	8-9 years		10-11 years		12-13 years	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
<i>Arithmetic</i>						
ϕ	.11	.98	.83	-.52	.92	.28
γ	.01	.90	.71	-.45	.46	.75
A'_{ROC}	.08	.94	.78	-.48	.95	.01
<i>Memory</i>						
ϕ	.99	.06	.87	.46	.84	.05
γ	.92	.08	.63	.69	-.25	.83
A'_{ROC}	.93	.05	.84	.34	.92	-.24
Eigenvalue	2.73	2.67	3.67	1.52	3.61	1.35
%Variance Explained	46	45	61	25	60	23

Note. A_{ROC} = Area under the Receiver-Operating-Characteristic (ROC) curve.

Table 4

Mean Better Strategy Selection Rates, Mean Selection Times (in ms), and Mean Execution Times (in ms) in Each Age Group for the Arithmetic and the Memory Tasks, in Experiment 2.

	8-9 year olds	10-11 year olds	12-13 year olds	<i>Means</i>
<i>Arithmetic</i>				
Better strategy selection rates	0.63 (.03)	0.76 (.03)	0.85 (.03)	.74 (.03)
Better strategy selection times	8199 (371)	6985 (380)	7742 (398)	7642 (320)
Better strategy execution times	7325 (524)	4574 (576)	5287 (582)	5729 (558)
<i>Memory</i>				
Better strategy selection rates	0.89 (.02)	0.91 (.02)	0.93 (.01)	0.91 (.01)
Better strategy selection times	8802 (607)	6009 (467)	4021 (336)	6278 (429)
Better strategy execution times	6809 (506)	4412 (554)	5795 (599)	5672 (523)

Note. Standard errors are in parentheses.

Table 5

Means and Tests of Metacognitive Sensitivity for the Three Age Groups and the Two Strategy Selection Tasks, in Experiment 2

	ϕ		γ		A'_{ROC}	
	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>
<i>Arithmetic</i>						
8-9 year olds	.09 (.03)	2.47*	.20 (.08)	2.42*	.54 (.02)	2.64*
10-11 year olds	.23 (.05)	4.52**	.42 (.14)	2.97*	.62 (.03)	3.62*
12-13 year olds	.17 (.04)	3.74**	.38 (.14)	2.69*	.57 (.02)	3.42*
All	.16 (.03)	6.16**	.34 (.07)	4.63**	.57 (.01)	5.30**
<i>Memory</i>						
8-9 year olds	.10 (.05)	1.94†	.24 (.17)	1.43	.56 (.03)	1.93†
10-11 year olds	.23 (.05)	4.64**	.55 (.14)	3.94**	.58 (.03)	2.97*
12-13 year olds	.23 (.06)	3.92**	.43 (.18)	2.43*	.61 (.03)	2.91*
All	.19 (.03)	5.94**	.41 (.09)	4.36**	.58 (.02)	4.49**

Note. *t* tests are two-tailed comparisons against chance: i.e., 0 for ϕ and γ ; 0.5 for Area under the Receiver-Operating-Characteristic (ROC) curve (A'_{ROC}). Standard errors are in parentheses.

† $p < .08$; * $p < .05$; ** $p < .001$

Table 6

Loadings of each Metacognitive Measure on the two Strategy Selection Tasks for Each Age Group, in Experiment 2

	8-9 years		10-11 years		12-13 years
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1
<i>Arithmetic</i>					
ϕ	.89	-.42	-.89	.42	-.93
γ	.89	-.43	-.77	.40	-.87
A'_{ROC}	.88	-.40	-.84	.39	-.90
<i>Memory</i>					
ϕ	-.57	-.78	-.85	-.48	-.91
γ	-.43	-.76	-.63	-.52	-.91
A'_{ROC}	-.42	-.79	-.83	-.33	-.76
Eigenvalue	3.06	2.35	3.89	1.10	4.65
%Variance Explained	51	39	65	18	77

Note. A_{ROC} = Area under the Receiver-Operating-Characteristic (ROC) curve.

Table 7

Mean Better Strategy Selection Rates, Mean Selection Times (in ms), and Mean Execution Times (in ms) in Each Age Group for the Arithmetic and the Memory Tasks, in Experiment 3.

	8-9 year olds	10-11 year olds	12-13 year olds	<i>Means</i>
<i>Arithmetic</i>				
Better strategy selection rates	0.83 (.01)	0.88 (.01)	0.90 (.01)	0.87 (.61)
Better strategy selection times	7070 (369)	6502 (415)	6055 (370)	6543 (225)
Better strategy execution times	6914 (615)	5150 (571)	4599 (354)	5554 (321)
<i>Memory</i>				
Better strategy selection rates	0.86 (.02)	0.87 (.01)	0.88 (.01)	0.87 (.01)
Better strategy selection times	5621 (422)	4592 (313)	3889 (427)	4701 (238)
Better strategy execution times	6570 (417)	5388 (441)	4426 (388)	5461 (258)

Note. Standard errors are in parentheses.

Table 8

Means and Tests of Metacognitive Sensitivity for the Three Age Groups and the Two Strategy Selection Tasks, in Experiment 3

	ϕ		γ		A'_{ROC}	
	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>	<i>M</i>	<i>t</i>
<i>Arithmetic</i>						
8-9 year olds	.25 (.06)	4.33**	.35 (.09)	2.49*	.60 (.03)	3.83**
10-11 year olds	.23 (.04)	6.48**	.28 (.08)	1.89*	.62 (.02)	6.25**
12-13 year olds	.39 (.05)	7.23**	.45 (.09)	3.59*	.70 (.03)	5.64**
All	.29 (.03)	9.79**	.36 (.05)	4.59**	.64 (.02)	8.45**
<i>Memory</i>						
8-9 year olds	.24 (.05)	5.24**	.39 (.08)	3.24*	.58 (.02)	3.83**
10-11 year olds	.31 (.06)	5.33**	.46 (.08)	4.06**	.66 (.03)	4.60**
12-13 year olds	.37 (.04)	8.48**	.42 (.11)	2.63*	.66 (.03)	5.62**
All	.31 (.03)	10.59**	.43 (.05)	5.64**	.63 (.02)	7.93**

Note. *t* tests are two-tailed comparisons against chance: i.e., 0 for ϕ and γ ; 0.5 for Area under the Receiver-Operating-Characteristic (ROC) curve (A'_{ROC}). Standard errors are in parentheses.

* $p < .05$; ** $p < .001$

Table 9

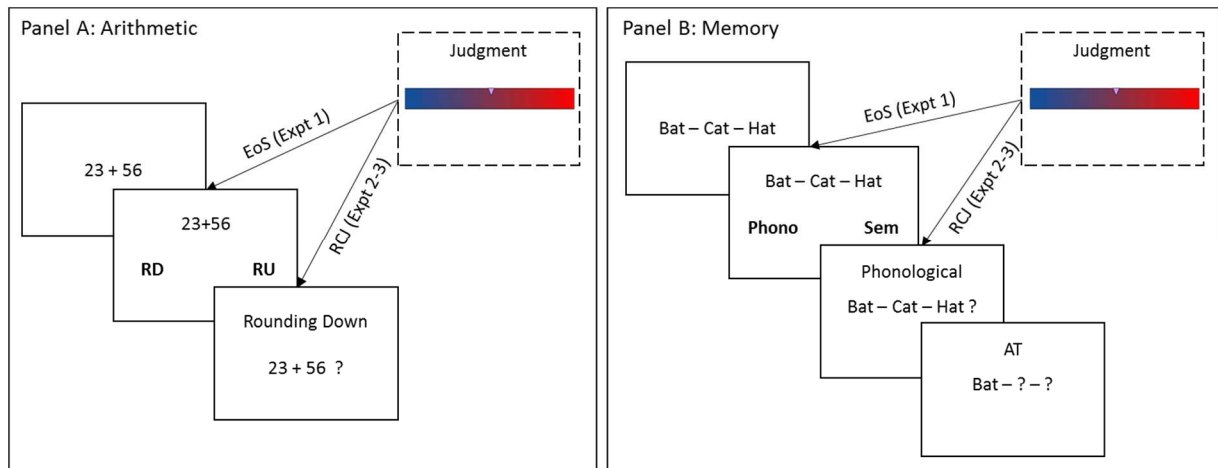
Loadings of each Metacognitive Measure on the two Strategy Selection Tasks for Each Age Group, in Experiment 3

	8-9 years		10-11 years		12-13 years
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1
<i>Arithmetic</i>					
ϕ	-.76	.62	-.90	.17	-.91
γ	-.70	.55	-.92	.14	-.87
A'_{ROC}	-.78	.49	-.71	.47	-.95
<i>Memory</i>					
ϕ	-.58	-.68	-.70	-.61	-.94
γ	-.57	-.77	-.64	-.62	-.83
A'_{ROC}	-.53	-.68	-.87	.24	-.84
Eigenvalue	3.19	2.25	3.69	1.19	4.77
%Variance Explained	53	37	61	20	80

Note. A_{ROC} = Area under the Receiver-Operating-Characteristic (ROC) curve.

Figure Captions

Figure 1. Detail of the experimental procedure for the arithmetic task (Panel A) and the memory task (Panel B), in Experiments 1, 2 and 3. Ease of Selection (EoS) judgments are required only in Experiment 1. Retrospective Confidence Judgments (RCJ) are required only in Experiments 2 and 3.



Appendix

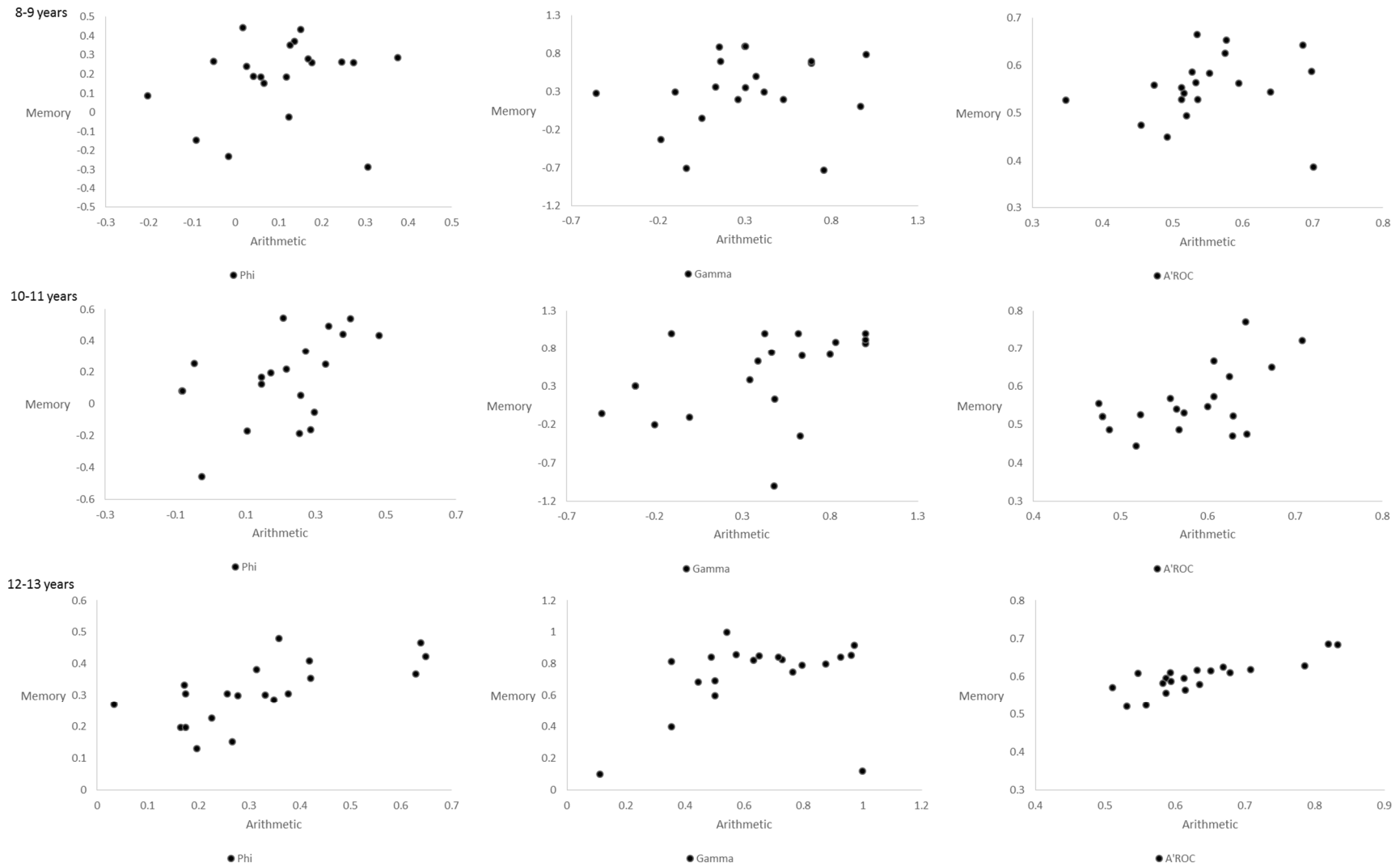


Figure A1. Correlational plots between the phi, the gamma, and the A'_{ROC} indexes for the three age groups in Experiment 1.

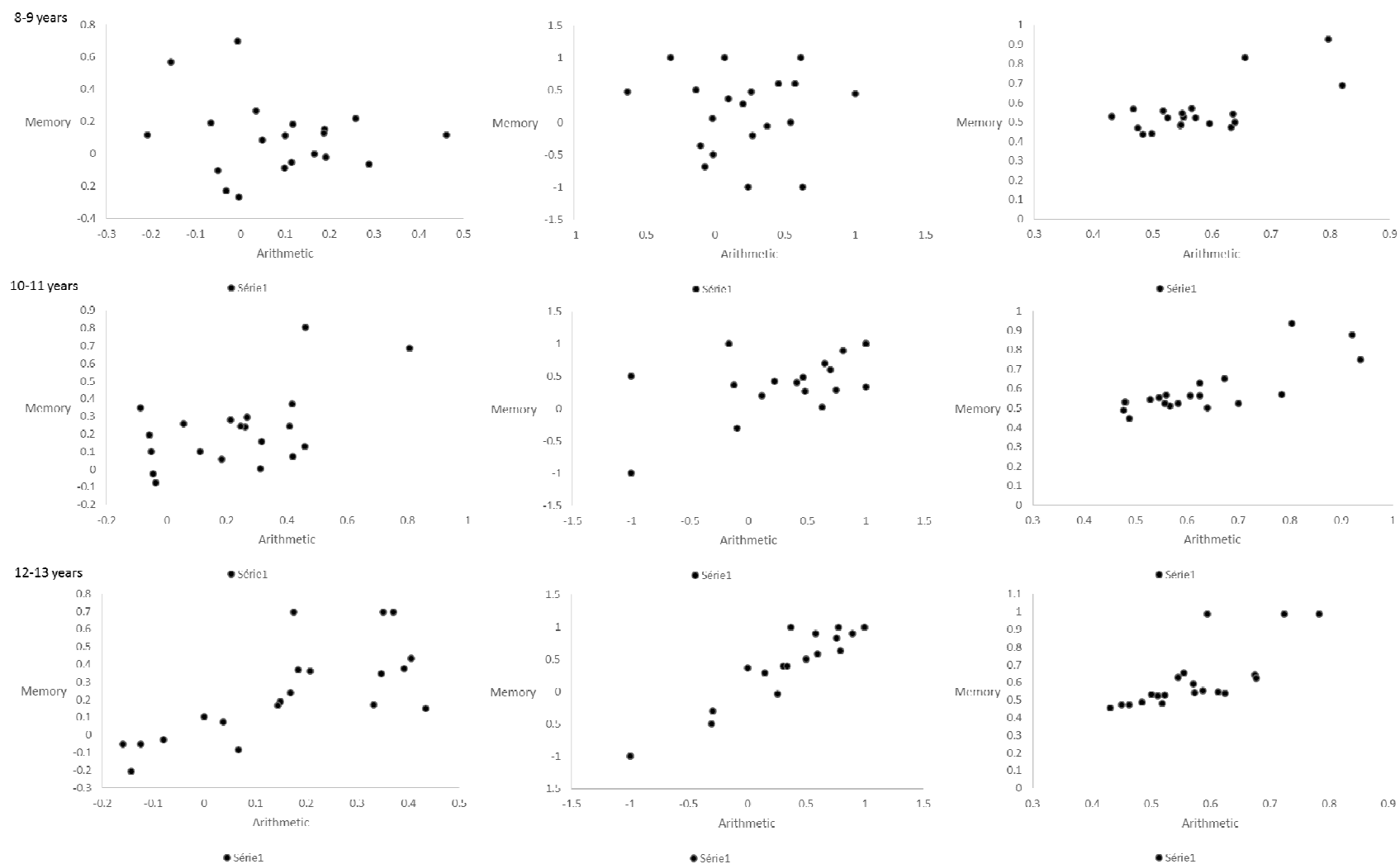


Figure A2. Correlational plots between the phi, the gamma, and the A'_{ROC} indexes for the three age groups in Experiment 2.

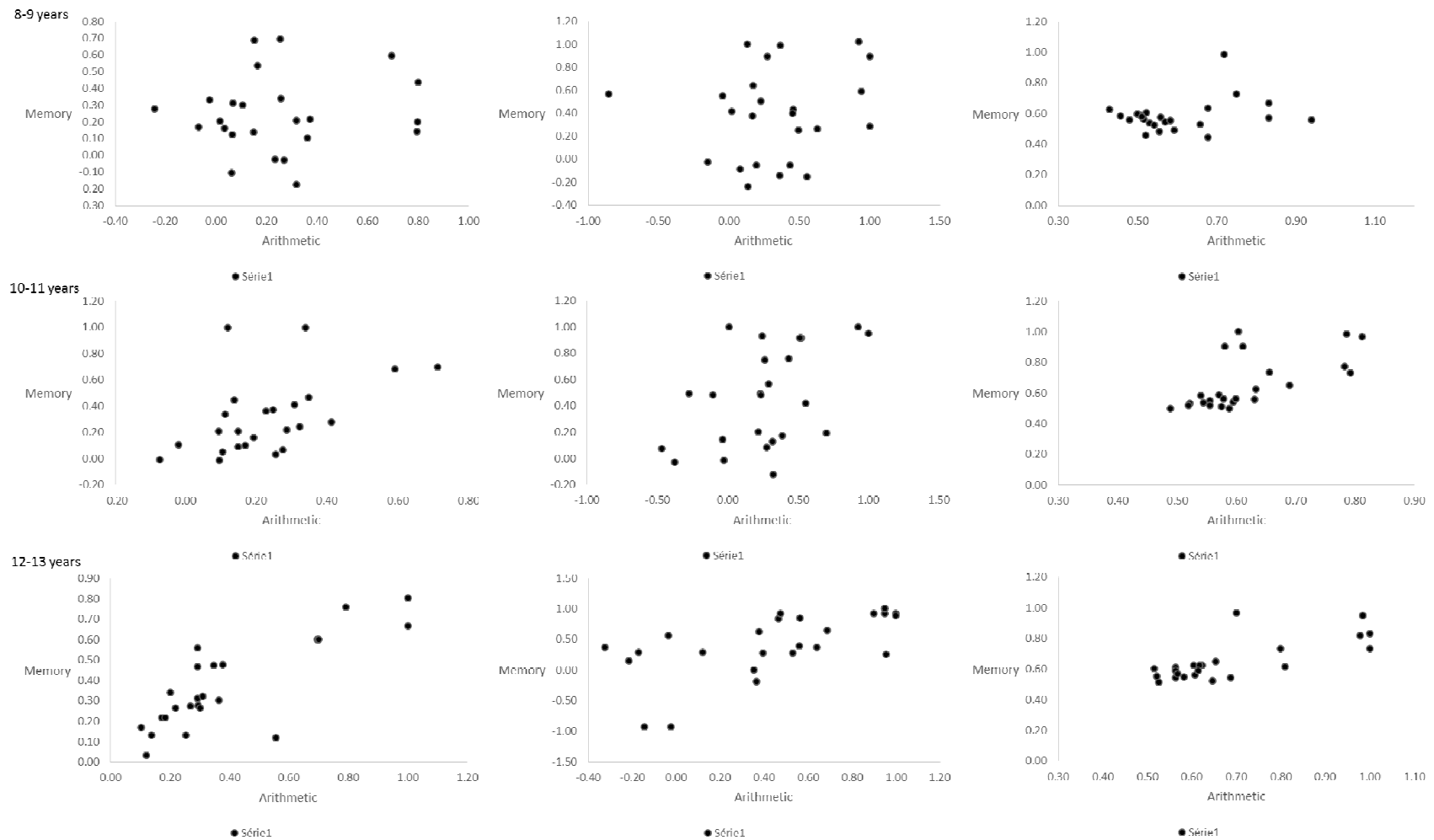


Figure A3. Correlational plots between the phi, the gamma, and the A'_{ROC} indexes for the three age groups in Experiment 3.