Effects of working memory updating on children’s arithmetic performance and strategy use: A study in computational estimation

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\textbf{A B S T R A C T}

The current study investigated how children’s working memory updating processes influence arithmetic performance and strategy use. Large samples of third and fourth graders were asked to find estimates of two-digit addition problems (e.g., 42 + 76). On each problem, children could choose between the rounding-down strategy (i.e., rounding both operands down to the closest decades) or the rounding-up strategy (i.e., rounding both operands up to the closest decades). Four tasks were used to assess updating. Analyses of strategy use revealed that children with more efficient updating showed higher levels of (a) strategy flexibility (i.e., they were less likely to use a single strategy on all or nearly all problems within a test block), (b) strategy adaptivity (i.e., they selected the better strategy overall more often and were more adaptive specifically on homogeneous and rounding-up problems), and (c) strategy performance (i.e., they tended to execute strategies more quickly, especially on homogeneous and larger problems). Finally, updating exerted a more important role for problem type effects in younger children than in older children. These findings have important implications for further understanding how working
memory updating processes influence children’s arithmetic performance and age-related differences therein. © 2019 Elsevier Inc. All rights reserved.

Introduction

Previous works have documented processes involved in children’s arithmetic strategy use. Thus, we know that both long-term memory and working memory processes influence children’s strategy performance. However, it is unknown whether one specific working memory process, namely updating, influences children’s performance and age-related changes. In the current study, we tested the hypothesis that updating processes of working memory play a crucial role in children’s arithmetic strategy use. To achieve this end, we adopted a strategy approach that enabled us to examine whether individual differences in children’s updating influence which strategy children use and how they execute available strategies while they accomplish a computational estimation task (i.e., finding approximate answers to arithmetic problems). We pursued this goal in the domain of computational estimation because previous works (a) already documented age-related changes in children’s performance while trying to find approximate answers to arithmetic problems and (b) showed that children use several strategies to accomplish computational estimation tasks. Before outlining the logic of the current work, we briefly review relevant findings on executive control (EC) processes and arithmetic strategy use and on children’s strategic development in arithmetic.

Executive control and arithmetic

EC involves higher-order mental operations concerned with the maintenance, manipulation, planning, monitoring, and regulation of other cognitive processes responsible for perception, memory, reasoning, problem solving, language, and action. These processes involve self-regulation, planning, organization, and the ability to initiate, maintain, switch, and stop sequences of complex behavior. Core EC processes include (a) inhibitory control (resisting habits, temptations, or distractions), (b) working memory (mentally holding and processing information), and (c) cognitive flexibility (for overviews, see Diamond, 2013; Miyake et al., 2000). Updating, one working memory process that is the focus of the current study, helps to keep track of relevant and irrelevant task components and is responsible for actively manipulating contents in working memory (Lehto, 1996; Morris & Jones, 1990).

A number of previous works has found that EC processes are crucial in arithmetic performance in general and in arithmetic strategy use in particular. For example, Imbo and Vandierendonck (2007) asked fourth, fifth, and sixth graders to solve simple addition problems such as 8 + 6 either in a single-task condition (solving only arithmetic problems) or in a dual-task condition (solving arithmetic problems and accomplishing a continuous choice reaction time task, taxing the central executive of working memory). Results revealed that children’s performance in the dual-task condition dropped significantly, especially in the youngest children (see Ai, Yang, Zhang, Si, & Liu, 2017, for similar results). As another example, Barrouillet and Lépine (2005) found that children with high memory spans tended to use retrieval more often than children with low memory spans. Both of these studies show that working memory processes are crucially involved in children’s strategy use. Finally, Lemaire and Lecacheur (2011) found that strategy choices and strategy execution were influenced by two specific EC processes, namely inhibition and flexibility. Children with better inhibition and cognitive flexibility were more likely to select the better strategy on each problem and to efficiently execute each available strategy when asked to find approximate sums for two-digit addition problems. Thus, it can be concluded that EC processes play a role in children’s arithmetic strategy use. However, it is unknown whether working memory updating, one specific EC process, is crucially involved in arithmetic strategy use, an issue that we pursued in the current study.

We pursued this issue in the context of computational estimation. Computational estimation consists in giving approximate answers to arithmetic problems without actually calculating the exact
answers but simplifying the calculation (e.g., via rounding the operands). Finding an approximate sum for an addition problem involves encoding the original problem, actively manipulating the operands by rounding the summands, holding the rounded numbers in working memory, and adding the rounded operands before providing an answer. In the current study, we hypothesized that updating processes are crucial to execute this series of processes. Indeed, updating consists in “coding incoming information for relevance to the task at hand and then appropriately revising the items held in working memory by replacing old, no longer relevant information with newer, more relevant information” (Miyake et al., 2000, p. 57). Hence, storing and retrieving intermediate results in and from working memory while solving computational estimation should be facilitated in children with more efficient updating processes. In addition, updating should be involved when activating available strategies in working memory and choosing among strategies as a function of problem characteristics by retrieving associations from long-term memory.

Although no studies have yet investigated how working memory updating is involved in participants’ strategy use in a computational estimation task, during past years various studies showed that of all EC processes, updating seems to be most strongly linked to arithmetic performance in general. For example, in a study with 11- and 12-year-old children, St Clair-Thompson and Gathercole (2006) identified high unique associations of a factor including updating and working memory span measures with mathematics scores in a principal component analysis. The mathematics score was operationalized by one mental and two written arithmetic tests. Although St Clair-Thompson and Gathercole did not use a computational estimation task to assess children’s arithmetic abilities, we expect performance specifically in the mental test to be highly linked to performance in computational estimation because mental manipulation of the task and mental addition are required when finding approximate sums for addition problems. As another example, a meta-analysis by Friso-van den Bos, van der Ven, Kroesbergen, and van Luit (2013) revealed a higher correlation between mathematics and updating than between mathematics and inhibition or shifting. Furthermore, a confirmatory factor analysis in second graders showed that the development of updating was strongly related to mathematical development, whereas inhibition and shifting did not predict arithmetic, when controlling for updating (van der Ven, Kroesbergen, Boom, & Leseman, 2012). Moreover, Lechuga, Pelegrina, Pelaez, Martin-Puga, and Justicia (2016) investigated the relative contributions of working memory updating and intelligence to academic attainment in fourth graders. In hierarchical regression analyses, they found that both variables made a unique contribution to the prediction of mathematical problem solving and arithmetical operations. Importantly, updating accounted for a larger amount of variance in both arithmetic performance variables. Again, the arithmetic scores comprised various math tasks such as simple addition, mental calculation, and number comparison, which are relevant subprocesses within computational estimation.

In sum, previous research found that EC processes crucially influence children’s arithmetic performance in the domain of strategies and age-related changes in this performance. This influence occurs via children with the most efficient EC processes using the best strategy more often and executing available strategies more efficiently. One of the important limitations of previous studies, however, is that none investigated the role of one EC process, namely updating. As a consequence, we do not know whether updating is, like other core EC processes, crucial in children’s arithmetic strategy use. The possibility that updating may be crucial for arithmetic strategy use has been discussed by several authors (e.g., DeStefano & LeFevre, 2004). However, no empirical data have documented this role. Therefore, the aim of the current study was to investigate the contribution of children’s working memory updating processes to their arithmetic performance as well as to their arithmetic strategy use. We adopted a strategy approach because previous studies established the crucial role of strategic aspects of children’s performance in arithmetic.

**Children’s strategic development in arithmetic**

An important factor in children’s academic performance in general, and in math in particular, is cognitive strategy use. A strategy can be defined as “a procedure or set of procedures for achieving a higher level goal or task” (Lemaire & Reder, 1999, p. 365). Previous research found that children use various strategies while performing arithmetic problem solving as well as many other cognitive
tasks. With increasing age, children tend to rely less on easier strategies, select the best strategy for a problem more often, and execute strategies more efficiently (for overviews, see Lemaire, 2017; Siegler, 2007). As previously outlined, an open question is whether these developmental effects can be accounted for by the development of cognitive control processes such as updating. Some previous research indicates that children's use of cognitive strategies is influenced by children's EC processes (Lemaire & Lecacheur, 2011).

Moreover, there is evidence that different problem features, such as problem size and problem type, influence participants' strategies and performance in arithmetic (LeFevre, Greenham, & Waheed, 1993; Lemaire, Lecacheur, & Farioli, 2000; Lemaire & Lecacheur, 2011). For example, participants perform better on problems with smaller magnitudes (e.g., 27 + 12) than on problems with larger magnitudes (e.g., 87 + 62). In addition, they choose the better strategy more often on homogeneous problems (i.e., problems for which unit digits of operands are either both smaller or both larger than 5) than on heterogeneous problems (i.e., problems for which the unit digit is smaller than 5 in one operand and larger than 5 in the other operand). Determining which strategy is better on each problem and executing strategies is known to place demands on EC resources (e.g., Lemaire & Lecacheur, 2011). Here we tested the hypothesis that EC plays a crucial role in arithmetic performance via its effects on strategy use and strategy execution by comparing how children with varying efficiency levels in EC accomplish our computational task. In addition, items were carefully constructed, in order to vary the demands on EC.

Above and beyond documenting empirical relations between EC and children's arithmetic, our findings were expected to contribute to theories of strategies. Several models of strategies have been proposed to account for children's strategy selection as well as their strategic development. These are the adaptive control of thought—rational (ACT-R) model by Lovett and Anderson (1996), the strategy selection learning (SSL) model by Rieskamp and Otto (2006), and the strategy choice and discovery simulation (SCADS) model by Shrager and Siegler (1998). These models have several common core assumptions. For instance, they assume that children select strategies on a trial-by-trial basis. This means that children select the strategy on each trial rather than a priori choosing one strategy to solve all or nearly all problems. In addition, models propose that when children are presented with a problem, they activate relative benefits and costs of available strategies and select the strategy with larger benefits and lower costs. Strategic development is commonly explained as the result of age-related changes in processes from learning experience. Such processes include “associative learning mechanisms” (Shrager & Siegler, 1998, p. 407), “reinforcement learning” (Rieskamp & Otto, 2006, p. 208), and “processing of experience-based information” (Lovett & Anderson, 1996, p. 169). Previous studies documented sources of interindividual differences during development such as inhibition and flexibility (e.g., Lemaire & Lecacheur, 2011). Models of strategic development have not been devised to test the role of these processes and, as a consequence, do not say much about them as an explanation for strategic development. However, as already mentioned, because previous empirical studies established that EC processes are crucial to strategic development, by investigating the role of working memory updating, the current study was expected to shed important light on theories of how strategic changes occur. Furthermore, we argue that EC processes contribute to existing models by explaining several components during strategy selection and execution. For example, to choose strategies on each trial, participants need to switch strategies from one trial to the next (Lemaire & Lecacheur, 2011). To achieve this, they need to inhibit the just executed strategy on a given problem, reactivate the set of available strategies in working memory, and choose among these strategies as a function of problem characteristics by retrieving associations from long-term memory. In addition, participants need to coordinate the set of processes involved in a given strategy during strategy execution, for which EC processes may be crucial.

In sum, previous theoretical and empirical works on arithmetic have shown that participants' performance is influenced by the strategies they use, the type of problems they solve, participants' age, and general processing resources such as working memory capacities and some EC processes (e.g., inhibition, flexibility). It is unknown how one type of EC processes, namely working memory updating, influences children's arithmetic performance and whether updating contributes to strategic processes in arithmetic and to differences in performance as a function of children's age and problem characteristics. We pursued these issues in the current study.
To examine relations between updating and arithmetic, we asked large samples of third and fourth graders to find approximate sums for two-digit addition problems (e.g., 42 + 76). On each problem, children could choose between two available strategies, namely the rounding-down strategy (i.e., rounding both summands down to the closest decades such as doing 40 + 70 = 110 for 42 + 76) and the rounding-up strategy (i.e., rounding both summands up to the closest decades such as doing 50 + 80 = 130 for 42 + 76). We included two types of problems, namely so-called homogeneous and heterogeneous problems. These two problem types were included following previous findings that children’s performance and strategies differ between these types of problems and because the problem type effect changes with age; children are more likely to select the better strategy on homogeneous problems than on heterogeneous problems, and this effect is larger in older children (Lemaire & Brun, 2014; Lemaire & Lecacheur, 2011). Moreover, half of the problems were so-called rounding-down problems (i.e., the use of the rounding-down strategy would lead to better estimates that are closer to the exact sum) and half were rounding-up problems (i.e., rounding up would lead to better estimates) because previous works showed that children select the better strategy more often on rounding-down problems and are faster when using the rounding-down strategy (Lemaire & Brun, 2016). To examine problem size effects, we used a wide range of exact sums (i.e., from 58 to 163).

We decided to investigate third and fourth graders following previous studies showing that important strategic changes occur in children of this age range (e.g., LeFevre et al., 1993; Lemaire & Lecacheur, 2011). Moreover, in German schools, where the data were collected, rounding rules and computational estimation are first introduced in third grade and further practiced in fourth grade. Therefore, if working memory updating is crucial in strategy use and strategic changes, it was expected that it would be most sensitively detected in third and fourth graders.

Most originally, we assessed children’s working memory updating functions with four updating tasks. An indicator of updating underlying all four tasks was extracted to obtain a more reliable and valid measure of updating. By combining measures of four different updating tasks, we minimized the influence of task-specific processes to address the so-called task impurity problem within the field of executive functions (Rabbitt, 1997). We tested the hypothesis that children with more efficient updating would choose the better strategy more often and execute strategies more efficiently. Another goal was to examine whether the efficiency of updating moderates effects of item characteristics (i.e., rounding-down/rounding-up problems, homogeneous/heterogeneous problems, and smaller/larger problems). Thus, we tested whether children with more efficient updating would show smaller problem size effects, smaller differences between rounding-up and rounding-down problems, and larger problem type effects.

Method

Participants

A total of 308 children were tested: 158 third graders (90 boys; age in months: \( M = 114.0, SD = 5.6, \) range = 102.4–138.7) and 150 fourth graders (80 boys; age in months: \( M = 126.1, SD = 5.2, \) range = 116.2–147.0). The study was conducted at the end of the school year. Children were recruited from 24 classes in 11 elementary schools in urban and suburban areas of the state of Hesse, Germany. The study was approved by the local ethics committee. Furthermore, parents provided written informed consent and participants gave their verbal assent.

Materials and procedure

All participants completed four updating tasks and a computational estimation task. Children took part in two sessions, each lasting approximately 45 min with an average of 8.5 days (SD = 5.7) in between sessions. The order of test administration was the same for all participants.
Children were tested in groups of 2–11 individuals ($M = 7.4, SD = 2.3$). They solved all tasks on tablet computers. Tasks were programmed with E-Prime 3.0. Instructions were presented verbally over headphones, and additional instructions were given when children did not respond or made errors during the first practice trials. Two experimenters were present for each group to answer children's questions and provide further explanations if needed.

**Working memory updating tasks**

Working memory updating was assessed with four different tasks to obtain a stable and purer measure of updating. These four tasks were the spatial keep track, day keep track, frog position updating, and color updating tasks.

The **spatial keep track** task (Dirk & Schmiedek, 2016) comprised 16 trials. On each trial, children were presented with either two or three differently colored fictitious creatures (i.e., monsters) at different positions on a 4 by 4 grid. Each of the two difficulty levels (i.e., two vs. three creatures) was presented 8 times. Children were asked to remember the initial positions of the creatures. The creatures disappeared after 3000 ms. Then, arrows matching the creatures' colors were successively presented in the center of the grid for 2500 ms with interstimulus intervals of 500 ms. Each arrow indicated that the creature of the corresponding color should move one block in the arrow's direction. Three arrows for two-creature trials and four arrows for three-creature trials were presented (i.e., three and four updating operations, respectively). Participants were asked to remember the new updated positions of all creatures and to reproduce the final positions on an empty grid at the end of each trial.

An arithmetic keep track task (Dirk & Schmiedek, 2016) was adapted and changed into a **day keep track** task to avoid an arithmetic confound in our measures of updating. Across 18 trials, participants were presented with one, two, or three distinct calendar pages. On each page, the German name for a weekday was written. Children were asked to remember the initial weekdays on the calendar pages. The names of the weekdays appeared for 3000 ms for one-calendar trials and for 4000 ms for two- and three-calendar trials. After displaying weekday names, a series of updating instructions (i.e., German words for **1 forward**, **2 forward**, **1 backward**, and **2 backward** and corresponding arrows) was presented on empty calendar pages for 3000 ms one at a time. Updating operations were presented with interstimulus intervals of 500 ms. Participants were asked to remember the updated weekdays for each calendar and to reproduce the final weekdays. The weekdays needed to be updated three times for one- and two-calendar trials and three or four times for three-calendar trials. Each of these three difficulty levels (i.e., one, two, or three-calendar trials) was presented six times.

Next, in the **frog position updating** task (LeFevre et al., 2009), participants were presented with movement sequences of three to seven distinct positions of a frog on an array of eight irregularly positioned water lily leaves. Children were then asked to indicate the last two, three, or four positions of the frog. Each of these three difficulty levels (i.e., remembering the last two, three, or four positions) was presented five times. Each position of the frog was displayed for 1750 ms with interstimulus intervals of 250 ms.

Finally, children performed 16 trials of a **color updating** task (Lee, Ng, Bull, Pe, & Ho, 2011). They were visually and verbally presented with sequences of four to eight colors one at a time. Children were asked to remember either the last two or three colors in eight trials each. Stimuli consisted of eight colors with monosyllabic names in German. Each color was presented for 1500 ms before it was covered for 500 ms and followed by the presentation of the next color.

The percentage of correctly remembered items in each of the four tasks was used as a measure of individuals' updating function. If more than half of the trials of a difficulty level were missing for a participant (e.g., missing at random due to program crashes), the subtest score was not calculated. Thus,

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1 Following one of the reviewers' comments, we tested the influence of the size of the group on children's strategy use. Analyses revealed that children in larger groups showed faster estimation latencies and that this effect was somewhat larger in fourth graders. However, including the size of the group as a predictor did not change the current main and important results. No effects of the size of the group were found on children's strategy flexibility or better strategy selection (see also the syntax script in the online supplementary material for the analyses with the size of the group included).
subtest scores were calculated for 249, 264, 262, and 275 children out of 277 children for the spatial keep track, day keep track, frog updating, and color updating tasks, respectively. The internal consistency of the updating tasks, as calculated by Cronbach’s alpha for two balanced parcels each, was high ($\alpha = .89, .85, .87$, and $.85$ for the spatial keep track, day keep track, frog position updating, and color updating tasks, respectively). Moreover, the internal consistency of the updating composite score, as calculated by the mean of all $z$-standardized parcels, was high ($\alpha = .89$).

To verify the factorial structure, we ran an exploratory factor analysis including the $z$ scores of the updating subtest parcels. The corresponding scree plot clearly indicated a structure with a single factor only. To obtain a task-nonspecific updating value, the factor scores of a factor analysis with a single factor were used for further analyses. We centered updating scores within grades; thus, a score of zero (0) in the following analyses reflects the updating function of an average child within his or her grade.

**Computational estimation task**

**Task stimuli.** Children worked on two sets of 21 two-digit addition problems each. Problems included operands ranging from 21 to 89; exact sums ranged from 58 to 163. One third of the problems were homogeneous problems, and two thirds of the problems were heterogeneous problems. Unit digits both were smaller than 5 (e.g., 52 + 63) in half the homogeneous problems and larger than 5 in the other homogeneous problems (e.g., 38 + 76). The unit digit of the first operand was smaller than 5 in the first operand and larger than 5 in the second operand in half of the heterogeneous problems (e.g., 41 + 27), and the reverse was the case in the other heterogeneous problems (e.g., 68 + 43).

Half the problems were so-called rounding-down problems (e.g., 42 + 61), where rounding both operands down to the nearest decades yielded better estimates (i.e., closer to the exact sum). The other problems were so-called rounding-up problems (e.g., 29 + 68), where rounding both operands up to the nearest decades yielded better estimates. Rounding-down and rounding-up problems were matched on mean exact sums ($M$s = 107.2 and 105.2 for rounding-down and rounding-up problems, respectively), on the number of problems requiring a carry over 100, and on their mean splits between unit digits from the nearest decades when rounding with the better strategy ($M = 7.2$ for both rounding-up and rounding-down problems). Moreover, rounding-down and rounding-up problems were matched on mean percentage deviations when solved with the better and poorer strategies. Thus, mean percentage deviations between correct sums and estimates for rounding-down problems were 7.3 (range = 2.8–13.8) when solved with the rounding-down strategy and 12.8 (range = 7.9–20.7) when solved with the rounding-up strategy. Mean percentage deviations between correct sums and estimates for rounding-up problems were 13.2 (range = 7.3–23.1) when solved with the rounding-down strategy and 7.5 (range = 2.2–12.7) when solved with the rounding-up strategy.

Finally, based on previous findings in arithmetic (for overviews, see Cohen Kadosh & Dowker, 2015; Gilmore, Göbel, & Inglis, 2018), we controlled the following factors. First, no operands had a 0 or 5 as unit digit (e.g., 20 + 63, 25 + 63). Second, sums of unit digits never equaled 10. Third, unit and decade digits were never the same within operands (e.g., 44 + 23). Fourth, unit or decade digits were never the same for both operands in a given problem (e.g., 32 + 62, 49 + 41). Fifth, no problems with reverse order of the operands from another problem were presented (e.g., if 68 + 24 was included, 24 + 68 was not). Sixth, no operand had its closest decade equal to 0, 10, or 100.

**Task procedure.** Children were told that they should give an approximate answer for each addition problem without actually calculating the exact sum. They were instructed to use one of two rounding strategies, either the rounding-down strategy (i.e., rounding both operands down to the nearest decades) or the rounding-up strategy (i.e., rounding both operands up to the nearest decades). The mixed-rounding strategy (i.e., rounding one operand up and the other operand down to the nearest decades) was not allowed. They were asked to use the better strategy for each addition problem. The better strategy was defined as the strategy that yielded the closest estimate to the exact sum. They were also asked to be as fast as possible.

Children were asked to indicate their answer to each problem on a touchscreen-based numpad. Strategies were not assessed directly by asking children which strategy they had used on each
problem. Rather, we inferred which strategy was used on each problem from given responses (e.g., a child was considered to have used the rounding-down strategy after providing 90 as a sum estimate for 41 + 58 or the rounding-up strategy after providing 110 as the estimate; and any other estimate was coded as “other”). The numpad consisted of keys with rounded numbers from 10 to 200 to prevent children from typing in exact sums or estimates with 5 as a unit digit. Prior to the computational estimation task, children were asked to enter eight verbally presented two-digit numbers (e.g., 60) on the numpad to ensure that they were familiar with the input modality. Then, children practiced on six training problems. They were provided with feedback on each practice problem regarding whether they had chosen one of the two allowed strategies to ensure that they were familiar with executing the rounding strategies. Although some children initially used the mixed-rounding strategy, all individuals had no difficulties with the procedure or with either rounding down or rounding up. Finally, problems were presented with varying response stimulus intervals (RSIs)\(^2\) from 600 to 2000 ms in random order.

**Data processing**

An entire test block of a participant (i.e., one set of 21 trials) was excluded from all further analyses if on at least one third of trials values were missing or responses did not match the result of one of the two available rounding strategies. Thus, both test blocks of 21 children and either the first or second test block of 33 children were excluded. In addition, the first trial of each test block was not considered in analyses. Moreover, trials of the computational estimation task were excluded from further analyses regarding their estimation times if the given answer did not match the result of one of the two available rounding strategies (thus, 558 trials were excluded).

To omit trials with extreme individual response times, \(z\)-standardized values of the estimation times were calculated within participants. Trials were excluded from estimation time analyses if the values exceeded 2.5 (thus, 299 trials were excluded) because they most likely resulted from children’s transient distraction from the task. To handle data of children with an extremely slow response pattern, we calculated \(z\)-standardized values of children’s mean estimation times within grades. Thus, 10 children were excluded from all further analyses because their \(z\) values exceeded 2.5, resulting in a sample size of 277 children.

Children’s strategy flexibility was analyzed for these 277 children. Because we decided to focus mainly on children’s flexible strategy use, we included only flexible test blocks in analyses of children’s better strategy selection and estimation latencies. Thus, the latter analyses were run for a sub-sample of 226 children with data on at least one flexible test block.

**Statistical method**

All analyses were run using RStudio. Children’s better strategy selection and strategy estimation latencies were examined with cross-classified multilevel models to allow for and to examine (a) between-participant variance and (b) between-item variance. The data have a two-level cross-classified structure, with trials nested within 42 items as well as within 226 participants. Only trials with valid strategy use (i.e., rounding down or rounding up) were considered.

Children’s dichotomous strategy selection variables were analyzed with logit models for binary responses. To be able to interpret effects in terms of probabilities that \(y = 1\) (e.g., that children used the better strategy on a given problem), we calculated the predicted probabilities of children’s strategy selection for the different values of predictors and report them in the following as percentages. We calculated the predicted probabilities as population-averaged probabilities by averaging over different simulated Level 2 random intercepts. Thus, percentages in Results can be interpreted as predicted probabilities that are true for the average of children and items with a certain predictor combination (see also Steele, 2009, for the calculation of predicted probabilities in logit models).

\(^2\) The variation of RSI is not the scope of the current article. Note however, that including RSI as a factor did not change the presented results.
Results

Effects of working memory updating on strategy selection

Strategy variability

To examine children’s variability in their strategy use, we calculated the percentage of the rounding-down strategy use for each participant and test block. A score of .60 indicates that the child used the rounding-down strategy on 60% of the problems within the test block. The distribution of these scores revealed a trimodal structure (see the vertical histogram in Fig. 1). This multimodal structure points to the existence of subgroups within the current data. The first subgroup consists of children in the center of the distribution approaching the problems of a test block in a flexible manner and adjusting strategies on a problem-by-problem basis; the further two subgroups share an inflexible approach and solve all or nearly all problems with the same strategy, either rounding down (i.e., high values of percentage use of the rounding-down strategy) or rounding up (i.e., low values of percentage use of the rounding-down strategy). To take the two approaches into consideration, we created a dichotomous inflexibility variable. Because the distribution of the percentage use of the rounding-down strategy revealed minima at about 90% and 10%, a test block was classified as being approached in an inflexible manner when 90% or more of problems were solved with either the rounding-down or rounding-up strategy.

Most third graders ($n = 75$) and fourth graders ($n = 123$) solved problems within both test blocks with a flexible approach. Thus, the current study replicates previous findings on within-participant strategy variability (Siegler, 2007). However, 43 third graders and 8 fourth graders used an inflexible approach on all problems. The remaining 28 children solved one test block with a flexible approach and solved the other test block with an inflexible approach. Because 60 first test blocks and 65 second test blocks were classified as inflexible, inflexibility did not merely stem from effects of task familiarization (i.e., children would show strategy inflexibility more frequently within earlier test blocks) or motivational decline and fatigue (i.e., children would show inflexibility more frequently within later test blocks).

Fig. 1. Relations between children’s percentage rounding-down strategy use and percentage better strategy selection. Note that jitter was added in the scatterplot to make overlapping data points visible. This resulted in some data points being displayed beyond 0.0 or 1.0.
Note that in 74% of inflexible test blocks, the most frequently used strategy was the rounding-down strategy (see Fig. 1). However, in the other 26% of inflexible test blocks, the dominant strategy was the more complex rounding-up strategy. This points to the fact that inflexibility did not merely stem from children choosing the easier strategy on each problem because it is associated with less costs. Rather, the avoidance of cognitive costs involved in the process of strategy selection and switching between strategies fits the data.

To test the effects of grade (i.e., third vs. fourth) and working memory updating on children's flexibility on each test block, a logistic multilevel model was fitted to the dataset. Results revealed that it was more likely that a test block was approached in an inflexible manner by a third grader than by a fourth grader (39% vs. 9%; $\beta = -2.86$, 95% confidence interval (CI) $[-5.19, -0.53]$, $p = .02$), and children with less efficient working memory updating tended to approach a test block in an inflexible manner more often than children with more efficient updating (average predicted probability (PP) for children with a standardized updating score of $+1$ SD, $PP_{+1SD} = 27\%$ vs. $PP_{-1SD} = 32\%$; $\beta = -0.95$, 95% CI $[-2.05, 0.15]$, $p = .09$).

Focus on test blocks with a flexible approach

Fig. 1 reveals qualitatively different subgroups. Very high values in the percentage use of a dominant strategy (i.e., classification as inflexible) are (a) likely linked to an approach in which children do not select strategies on a trial-by-trial basis and (b) necessarily tied to a better strategy selection at about 50%, whereas in flexible test blocks the adaptivity generally is clearly higher. Because analyses regarding children's strategy use, therefore, would be distorted when including test blocks that were approached in an inflexible way, we included only flexible test blocks with a dominant strategy use of less than 90% in analyses of children's better strategy selection and estimation latencies. Thus, the following analyses were run for a subsample of 226 children (i.e., 94 third graders and 132 fourth graders) with data on at least one flexible test block.

Better strategy selection

The next analysis aimed at determining whether better strategy selection varied with participant and problem characteristics. Better strategy selection was coded 1 if children selected the better strategy on a problem (i.e., using the rounding-down strategy on rounding-down problems or the rounding-up strategy on rounding-up problems) and 0 otherwise. A logistic cross-classified multilevel model was fitted to the dataset to test the effects of grade (third vs. fourth), working memory updating, problem type (homogeneous vs. heterogeneous), problem size (size of the exact sum), and rounding type (rounding down vs. rounding up).

Fourth graders were more likely to select the better strategy than third graders ($PP = 86\%$ vs. $72\%$; $\beta = 0.65$, 95% CI $[0.45, 0.84]$, $p < .001$), and children with more efficient updating were more likely to use the better strategy than children with less efficient updating ($PP_{+1SD} = 84\%$ vs. $PP_{-1SD} = 74\%$; $\beta = 0.49$, 95% CI $[0.29, 0.68]$, $p < .001$) (see also Fig. 2A). Interestingly, it was equally likely for a third grader with updating $1$ SD above average to choose the better strategy ($PP = 78\%$) as for a fourth grader with updating $1$ SD below average ($PP = 82\%$). The Grade $\times$ Updating interaction was not significant ($\beta = 0.06$, 95% CI $[-0.13, 0.26]$, $p = .52$). Moreover, children were more likely to use the better strategy on homogeneous problems than on heterogeneous problems ($PP = 85\%$ vs. $72\%$; $\beta = -0.64$, 95% CI $[-0.79, -0.49]$, $p < .001$). Importantly, the Grade $\times$ Problem Type interaction ($\beta = -0.24$, 95% CI $[-0.32, -0.16]$, $p < .001$) and the Updating $\times$ Problem Type interaction ($\beta = -0.12$, 95% CI $[-0.20, -0.03]$, $p = .006$) were significant. This occurred because the effect of heterogeneous versus homoge-

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3 Note that the change of predicted probabilities with different problem types is numerically comparable in children with less efficient updating ($PP_{\text{homogeneous}} = 81\%$ vs. $PP_{\text{heterogeneous}} = 67\%$) and in children with more efficient updating ($PP_{\text{homogeneous}} = 91\%$ vs. $PP_{\text{heterogeneous}} = 78\%$); however, the significant interaction effect reveals that the problem type effect is larger in children with more efficient updating. This occurs because the logit model accounts for the fact that differences of predicted probabilities on the restricted scale from 0 to 100% are less likely in the upper and lower ranges close to 0% and 100%. Thus, the model considers that changes in probabilities are located in different ranges on the restricted probability continuum from 0 to 1 and does not solely compare numerical changes (see also Jaeger, 2008).
neous problems was larger in older children than in younger children and was larger in children with more efficient updating (see Fig. 2 B and C and Table 1). The Grade × Updating interaction \((\beta = -0.02, 95\% \text{ CI } [-0.11, 0.06], p = .64)\) was not significant.

The main effect of rounding type was not significant \((\beta = -0.03, 95\% \text{ CI } [-0.16, 0.11], p = .59)\), but the interaction effects Grade × Rounding Type \((\beta = 0.13, 95\% \text{ CI } [0.06, 0.19], p < .001)\) and Updating × Rounding Type \((\beta = 0.07, 95\% \text{ CI } [0.01, 0.14], p = .04)\) were significant. This occurred because only younger children were more likely to select the better strategy on rounding-down problems than on rounding-up problems, whereas older children chose the better strategy on rounding-down and rounding-up problems equally often (see Fig. 3A and Table 2). Similarly, the effects of type of rounding problems on better strategy selection were larger in children with less efficient updating than in children with more efficient updating (see Fig. 3B and Table 2). The three-way interaction of Grade × Updating × Rounding Type \((\beta = -0.01, 95\% \text{ CI } [-0.07, 0.06], p = .87)\) was not significant.

All main and interaction effects including problem size were nonsignificant, with effect estimates close to 0 and narrow confidence intervals: problem size \((\beta = -0.00, 95\% \text{ CI } [-0.05, 0.04], p = .90)\), Grade × Problem Size \((\beta = -0.01, 95\% \text{ CI } [-0.03, 0.02], p = .59)\), Updating × Problem Size \((\beta = 0.00, 95\% \text{ CI } [-0.02, 0.03], p = .76)\), and Grade × Updating × Problem Size \((\beta = 0.00, 95\% \text{ CI } [-0.02, 0.03], p = .88)\).

### Table 1

<table>
<thead>
<tr>
<th>Problem type</th>
<th>Grade</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Third</td>
<td>Fourth</td>
<td>Mean</td>
</tr>
<tr>
<td>Less efficient updating (-1 SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
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<td>90</td>
<td>81</td>
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<tr>
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<td>67</td>
</tr>
<tr>
<td>Mean</td>
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<td>82</td>
<td>74</td>
</tr>
<tr>
<td>More efficient updating (+1 SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>97</td>
<td>91</td>
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<tr>
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<td>84</td>
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<tr>
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<td>84</td>
</tr>
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<td>Mean</td>
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<td>85</td>
</tr>
<tr>
<td>Heterogeneous</td>
<td>67</td>
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<td>72</td>
</tr>
<tr>
<td>Mean</td>
<td>72</td>
<td>86</td>
<td>79</td>
</tr>
</tbody>
</table>

*Note.* Unlike in an analysis of variance, children were not split into subsamples with less or more efficient updating, but the effect of updating was modeled continuously. For illustration, predicted probabilities are shown for children with updating processes 1 SD above average and 1 SD below average.
Effects of working memory updating on estimation latencies

A cross-classified multilevel model was fitted to the dataset to test the effects of grade (third vs. fourth), working memory updating, problem size (size of the exact sum), problem type (homogeneous vs. heterogeneous), and the strategy used (rounding down vs. rounding up) on children's estimation latencies on each problem. The influence of the predictors within the linear multilevel model can be calculated the same way as in multiple regressions by multiplying beta coefficients with the corresponding predictor values. Thus, estimation latencies can be derived by simple addition of beta coefficients, with all dummy variables being coded \( /C0 1/+1 \) and a change of 1 representing a change of 1 SD for updating and a change of 10 units for the exact sum. The reported influences on estimation latencies are true for an average child and an average item.

Because the fixed intercept was \( \beta = 12.68, 95\% \text{ CI} [12.10, 13.26] \), children took on average 12.7 s to estimate a problem and fourth graders were faster than third graders (12.1 vs. 13.2 s; \( \beta = -0.55, 95\% \text{ CI} [-1.06, -0.05], p = .04 \)). Moreover, children were faster on homogeneous problems than on heterogeneous problems (11.8 vs. 13.6 s; \( \beta = 0.90, 95\% \text{ CI} [0.58, 1.22], p < .001 \)), but this effect was qualified by both a Grade × Problem Type interaction (\( \beta = 0.31, 95\% \text{ CI} [0.15, 0.47], p < .001 \) and an Updating × Problem Type interaction (\( \beta = 0.21, 95\% \text{ CI} [0.04, 0.38], p = .01 \)). This occurred because differences in estimation times between heterogeneous and homogeneous problems were larger for
older children and for children with more efficient updating than for other children. Indeed, fourth graders were on average 2.4 s faster on homogeneous problems than on heterogeneous problems, whereas third graders were only 1.1 s faster. Similarly, children with updating 1 SD above average were 2.2 s faster on homogeneous trials than on heterogeneous trials, whereas children with updating 1 SD below average were only 1.4 s faster. Interestingly, the Grade x Updating x Problem Type interaction was significant ($\beta = -0.18$, 95% CI $[-0.34, -0.01]$, $p = .04$). This occurred because the influence of updating functions on the problem type effect was larger in third graders than in fourth graders (see Fig. 4). Indeed, in third grade, children with updating 1 SD below average were on average only 0.4 s faster on homogeneous problems than on heterogeneous problems (corresponding difference in latencies was 1.9 s in children with updating 1 SD above average). In contrast, these differences were almost the same for fourth graders with updating 1 SD below average (2.4 s) and above average (2.5 s). Thus, more efficient updating processes specifically facilitated third graders’ performance on homogeneous problems.

Furthermore, children were slower on larger addition problems (on average + 0.34 s for a 10-unit increase of the exact sum; $\beta = 0.34$, 95% CI [0.24, 0.45], $p < .001$). Importantly, this problem size effect interacted with children’s updating processes ($\beta = -0.08$, 95% CI $[-0.14, -0.03]$, $p = .003$). This occurred because children with more efficient updating were less influenced by problem size. Thus, children with updating 1 SD above average would slow down by only 0.26 s for a 10-unit increase of the exact sum, whereas children with updating 1 SD below average would slow down by 0.42 s. In addition, children were faster when using the rounding-down strategy than when using the rounding-up strategy (12.2 vs. 13.2 s; $\beta = 0.49$, 95% CI [0.19, 0.80], $p = .003$).

No other effects were significant: updating ($\beta = -0.43$, 95% CI $[-0.95, 0.09]$, $p = .10$), Grade x Updating ($\beta = 0.20$, 95% CI $[-0.31, 0.72]$, $p = .45$), Grade x Problem Size ($\beta = -0.03$, 95% CI $[-0.09, 0.02]$, $p = .24$), Grade x Updating x Problem Size ($\beta = 0.03$, 95% CI $[-0.02, 0.08]$, $p = .31$), Grade x Strategy Used ($\beta = -0.01$, 95% CI $[-0.18, 0.15]$, $p = .87$), Updating x Strategy Used ($\beta = -0.08$, 95% CI $[-0.25, 0.09]$, $p = .34$), and Grade x Updating x Strategy Used ($\beta = -0.05$, 95% CI $[-0.22, 0.11]$, $p = .52$).

Discussion

In this study, we examined the contributions of children’s working memory updating to their arithmetic performance and behavior with a strategy perspective. Large samples of third and fourth graders were asked to estimate sums of two-digit addition problems by rounding both operands either down or up to the nearest decades. Children’s strategy selection and strategy execution on problems of
varying difficulties were examined with a developmental perspective. Within recent decades, various works documented age improvements in children's strategy selection and execution (for overviews, see Lemaire, 2017; Siegler, 2007). In the current study, we replicated findings on item-related effects as well as age-related improvements in children's better strategy selection and strategy execution. Like in previous studies, we found that age-related changes in better strategy selection were modulated by the type of problems children solved.

Most important and unique, we examined how children's strategy use was influenced by working memory updating processes. Previous research found that executive functions influence children's strategies as well as age-related changes in strategic behaviors (Ai et al., 2017; Barrouillet & Lépine, 2005; Imbo, Duverne, & Lemaire, 2007; Imbo & Vandierendonck, 2007; Lemaire & Lecacheur, 2011). However, no previous data documented how efficiency of working memory updating processes influences children's arithmetic strategy use. The current data showed that efficient updating contributes to children's better strategy selection and strategy execution and that the relations between children's arithmetic performance and updating change with children's age and problem characteristics. We next discuss the implications of these findings.

Role of working memory updating processes in children's arithmetic strategy use

The current results show that individual differences in children's working memory updating processes contribute to three aspects of arithmetic strategy use: strategy flexibility, better strategy selection, and strategy execution.

Regarding children's strategy flexibility, large samples of third and fourth graders enabled us to identify two qualitatively distinct subgroups. In one group, showing strategy variability, children used the two available strategies in a flexible manner. In the other, smaller group, children used a dominant strategy on all or nearly all problems. Results revealed that children with more efficient updating were slightly more likely to use the two available strategies. This might be best explained by assuming that more EC resources facilitated the execution of processes crucial for trial-by-trial strategy selection (i.e., reactivating both strategies in working memory, analyzing problem features to determine which strategy is the best, and choosing the better strategy before executing it). In a study by Lemaire, Luwel, and Brun (2017), fifth and seventh graders were asked to estimate sums in conditions where only one strategy was available or two strategies were available. On each problem, children were told which strategy to execute. Results showed that children found estimates more quickly when they were using a single strategy rather than two strategies. The authors explained these findings in terms of lower demands placed on working memory and EC processes in the one-strategy condition.

In the current study, children with more efficient updating were more likely to select the better strategy on a problem-by-problem basis than children with less efficient updating. This relation was qualified by these children (a) using the rounding-up strategy more often and (b) being specifically adaptive on homogeneous problems. Moreover, we found that children with more efficient updating were specifically faster on (a) larger addition problems and (b) homogeneous problems.

We can only speculate about which mechanisms underlie the contribution of updating to these specific effects. We argue that these findings can be explained by associative processes. As commonly proposed in models of strategies (Payne, Bettman, & Johnson, 1993; Rieskamp & Otto, 2006; Shrager & Siegler, 1998), the mechanisms underlying strategy selection are based on the activation of costs and benefits of available strategies when being presented with a problem. In the current study, the two available strategies were the rounding-down and rounding-up strategies. Regarding cognitive costs, the rounding-up strategy requires more complex processes (i.e., rounding up the first operand, holding the rounded decade in working memory, executing the same procedure for the second operand, and adding the two updated decades) than the rounding-down strategy (i.e., solely adding the decade units). For children with more efficient updating, the more complex procedures of the rounding-up strategy entail costs that are smaller in relation to their available updating resources, whereas for children with less efficient updating, those relative costs are higher. Hence, in the former group the trade-off between relative costs and benefits is resolved in favor of the more complex procedures more often, leading these children to use the rounding-up strategy more adaptively with the benefit of a more accurate estimate.
In addition, the current study showed that main and interaction effects involving problem type were even larger than the corresponding effects involving rounding type; homogeneous problems were more often solved with the better strategy and were solved more quickly than heterogeneous problems, and this problem type effect interacted with age and updating. When being presented with a problem, it highly depends on children’s past learning experience whether costs and benefits of strategies are associated with the problem characteristics (Rieskamp & Otto, 2006; Shrager & Siegler, 1984). Children need to learn which strategies are available. Through experience, they learn to associate which strategy is most adaptive for certain problem characteristics, thereby being associated with larger benefits (e.g., that rounding up two-unit digits with unit digits larger than 5 would lead to a more accurate estimate than rounding down), and they experience which rounding strategy demands more cognitive effort, thereby being associated with larger costs. It is assumed that associations between strategies and certain problem features are strengthened as a result of learning experience and repeated use of algorithms (Shrager & Siegler, 1984), which explains the effect of children being more likely to select the better strategy and showing smaller estimation latencies on homogeneous problems than on heterogeneous problems; only for homogeneous problems could children form associations between problem features and the available strategies (i.e., rounding-down and rounding-up strategies), whereas heterogeneous problems would be associated with the mixed-rounding strategy, a strategy that was not allowed in the current study. The finding that children with more efficient working memory updating were specifically more accurate and faster on homogeneous problems is in line with the assumption that the “WM [working memory] system … utilizes various control processes that are needed to maintain information in WM and to build strong and durable memories in LTM [long-term memory]” (Unsworth, 2019, p. 81). Theoretical models (Barrouillet, Bernardin, & Camos, 2004; Gavens & Barrouillet, 2004) and empirical works (Barrouillet & Lépine, 2005; Unsworth, Brewer, & Spillers, 2013) on the relation between working memory and long-term memory support the notion that working memory processes contribute to associations in long-term memory being established and to existing associations being accessed. Therefore, it can be assumed that children with more efficient working memory have had an advantage in forming associations prior to the estimation strategy experiment and that during the experiment they had an advantage in retrieving those established associations for familiar homogeneous problems. This enabled them to access the associations for the better strategy more often and faster.

Importantly, contributions of updating processes to children’s problem type effect seem to differ between grades. In fourth grade, homogeneous problems were on average solved more than 2 s faster than heterogeneous problems, and this time advantage was independent of children’s updating efficiency. In contrast, in third grade, the solution time advantage of homogeneous problems depended on children’s updating efficiency. For third graders with efficient updating, a large estimation latency advantage of homogeneous problems over heterogeneous problems was found (like in fourth graders). In contrast, for third graders with less efficient updating, estimation times for homogeneous problems were nearly as slow as those for heterogeneous problems. A plausible explanation lies in different levels of associative learning for third versus fourth graders due to differences in formal training and education (Shrager & Siegler, 1984); all fourth graders, even those with less efficient updating, could already establish associations between familiar homogeneous problems and beneficial strategies minimizing the difference between estimates and exact sums because they had practiced rounding and estimation for more than a year. In contrast, for third graders, estimating approximate sums is a relatively novel task. For those with more efficient updating, the limited experience seems to have been sufficient to form associations between problem features and rounding strategies so that they could solve homogeneous problems faster than heterogeneous problems with the unfamiliar requirement of rounding both operands either down or up.

Note that opposite results regarding the interaction between children’s updating processes and problem type could also have been expected. Indeed, updating could be expected to be more relevant for harder (i.e., heterogeneous) problems than for simpler (i.e., homogeneous) problems. Recall that children were not allowed to use the mixed-rounding strategy that would be the dominantly associated strategy for heterogeneous problems. As mentioned above, EC processes are likely involved in two different stages during strategy use: (a) in the consolidation of long-term memory associations during prior learning processes and (b) during the processing of the current task. As revealed by
the main effects, efficient updating processes facilitate the processing of current problems in general. Furthermore, updating especially facilitates working on homogeneous problems, indicating that updating influenced the past consolidation of long-term associations and facilitates the current retrieval of these associations. Because on heterogeneous trials the dominantly associated strategy must be inhibited to select between the only available rounding strategies here (rounding down and rounding up), inhibition of the mixed-rounding strategies might be most relevant on these heterogeneous problems.

Finally, results revealed that children with more efficient updating slowed down less on larger addition problems than children with less efficient updating. Existing theories on the development of underlying procedures for (simple) addition are somehow inconsistent. It has long been assumed that age-related decreases in solution times for additions result from children using retrieval more often (Ashcraft, 1982; Siegler, 1987). This has lately been challenged by the assumption that addition always stems from unconscious counting procedures (Thevenot, Barrouillet, Castel, & Uittenhove, 2016). Even though there still remain open questions regarding underlying procedures for addition, our results indicate that updating processes facilitate children’s addition specifically for larger problems—whether via the more frequent use of retrieval or more efficient counting procedures.

In sum, the current study is the first to reveal that one EC process that had not been investigated yet, namely updating, plays an important role in children’s arithmetic strategies and performance. The findings on the contribution of children’s updating processes, especially on complex problems (i.e., rounding up and larger problems), support the notion of working memory to facilitate mental calculations that involve multiple steps (Hitch, 1978). Updating processes, therefore, should play an even larger role in more complex arithmetic that is not limited to two-digit addition problems estimation.

Implications

The findings of the current study have important theoretical implications for strategy choice models. Existing models (Payne et al., 1993; Rieskamp & Otto, 2006; Shrager & Siegler, 1998) share common assumptions such as the activation of associated costs and benefits during strategy selection. However, the models do not assume that strategy selection requires EC processes. Various works have already suggested that cognitive components, such as inhibition and shifting, should be added (Lemaire & Lecacheur, 2011; Luwel, Schillemans, Onghena, & Verschaffel, 2009). The current study strengthens this case by revealing that another executive function, namely working memory updating, contributes to children’s better strategy selection. Although the underlying mechanisms of the link between updating processes and strategy selection and execution need further research, it can be speculated that advantages in the consolidation and retrieval of associated costs and benefits of available strategies play an important role. We argue that updating could be included in existing models as influencing the relative importance or weights of associated costs and benefits to the person, similar to weighted additive heuristics (see also Payne et al., 1993). That is, associated costs due to the complexity of strategy operations can be compensated by efficient cognitive processes such as updating.

Together with previous studies showing effects of other EC processes on children’s strategy use (e.g., Barrouillet & Lépine, 2005; Lemaire & Lecacheur, 2011), the current findings raise several issues that need to be addressed in future research. One major limitation of the current and previous works is that the data cannot rule out the possibility that other executive functions or general cognitive abilities are involved in strategies and strategic changes. Indeed, several studies with participants of different age groups could consistently find that the performance in each executive function task can be decomposed into a contribution of the so-called common executive function and a unique contribution of the particular executive function (see also Miyake & Friedman, 2012). That is, when assessing updating, the score contains variance best explained by a general factor that is common to all executive functions and variance that is unique to updating. Miyake and Friedman (2012) defined the common executive function as the “ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing” (p. 11). This ability is essential to enable participants to engage in other specific processes. Hence, it is fair to expect that some variance in our updating score is shared with a common executive function factor underlying interindividual differences. In the current data, we cannot differentiate between these sources of variance or test
the assumption. However, we expect specific executive components to be more relevantly involved in different subprocesses of arithmetic problem solving than others. Because updating processes contain the active manipulation of information in working memory as well as the access to information from long-term memory, updating-specific abilities should be specifically required when retrieving strategy–problem associations from long-term memory and mentally rounding and adding up manipulated operands within a computational estimation task. In turn, the common factor should be the key to maintain the available strategies and inhibit invalid strategies such as mixed rounding for heterogeneous problems.

Going on from this, it would be important to empirically assess the relative contributions of distinct EC processes (shifting, inhibition, and updating) to strategy selection and performance as well as how these contributions change with age. Furthermore, it would be important to investigate whether different EC processes account for different experimental effects such as efficient shifting processes specifically accounting for smaller strategy switch costs or repetition benefits during strategy execution and updating processes specifically accounting for differences in strategy selection due to associative procedures. From a theoretical perspective, such comparative research could answer whether strategy models should include one or several parameters for EC processes to account for individual differences in strategy selection and execution.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2019.04.003.

References


