Age-related changes in children’s executive functions and strategy selection: A study in computational estimation

Patrick Lemaire*, Mireille Lecacheur

Univrsité de Provence & CNRS, Marseille, France

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ABSTRACT

Third, fifth, and seventh graders selected the best strategy (rounding up or rounding down) for estimating answers to two-digit addition problems. Executive function measures were collected for each individual. Data showed that (a) children’s skill at both strategy selection and execution improved with age and (b) increased efficiency in executive functions contributed significantly to age-related improvement in children’s strategy selection skill. These findings have implications for understanding of age-related differences in computational estimation, strategy selection processes, and mechanisms of strategic development in children.

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In this study, we examine the role of executive functions (EFs) in children's arithmetic strategy selection and in its development. Specifically, we investigate whether age-related changes in children’s executive functions are related to age-related changes in their strategy selection skills. We chose the domain of mathematical cognition because it is one in which strategic variations in general, and strategy selection in particular, have previously been investigated in great detail. Further, findings in this domain usually generalize to other cognitive domains and tasks in which participants use multiple strategies and select them on a trial-by-trial basis (Siegler, 1996). Before describing the present study, we review previous findings on development in children’s arithmetic strategies, age changes in EFs, and relations between EFs and arithmetic strategy and performance.

1. Strategic development in arithmetic

Cognitive strategies greatly influence the development of children’s mathematical skills. A strategy can be defined as “a procedure or a set of procedures for achieving a higher level goal or task” (Lemaire &
Reder, 1999). Previous research has found that children use varying strategies to accomplish cognitive tasks and select them on a trial-by-trial basis. They may thereby adapt flexibly in different contexts to inherent task characteristics, such as problem difficulty, and to situational demands, such as the need to answer quickly and/or accurately. With age, children use the most efficient and problem-appropriate strategies increasingly often, and they execute them more and more efficiently. These phenomena occur in many cognitive domains (Siegler, 1996) in addition to arithmetic (Barrouillet, Mignon, & Thevenot, 2008; Beishuizen, Van Putten, & Van Mulken, 1997; Blöte, Van der Burg, & Klein, 2001; Fuson, 1990; Kuhn & Pease, 2009; Lemaire & Calliès, 2009; Lemaire & Siegler, 1995; Lucangeli, Tressoldi, Bendotti, Bonanomi, & Siegel, 2003; Luwel, Lemaire, & Verschaffel, 2005; Siegler, 1988). A key developmental question is how children select the most efficient strategies more frequently as they grow older.

Several theories have been proposed to account for strategy selection and children's strategic development. Computational models (Lovett and Anderson's 1996 ACT-R model; Lovett and Schunn's 1999 RCCL model; Payne, Bettman, and Johnson's 1993 adaptive decision maker model; Rieskamp and Otto's 2006 SSL model; and Siegler and Arraya's 2005 SCADS* model) share several core assumptions regarding strategy choices and execution. All propose that choosing among multiple strategies involves associative mechanisms, such as activating relative costs/benefits of each strategy and selecting the one that works best on the basis of problem and strategy characteristics. All models assume that strategies including fewer and/or simpler procedures (e.g., solving arithmetic problems like $3 \times 4$ directly from memory) are easier to execute than ones involving more numerous and/or more complex procedures (e.g., adding 3 four times). These assumptions proved sufficient to account for most previous findings on strategy choice and execution.

However, these models do not account for several phenomena related to strategy and strategic development. For example, children sometimes use fewer strategies even when they know and can use all available strategies. It is also unknown why relative strategy efficacy does not fully account for strategy choice, or why children sometimes continue to use a strategy when an alternative is slightly faster and/or more accurate (Luwel, Verschaffel, Onghena, & De Corte, 2003; Siegler & Lemaire, 1997). An Einstellung effect, in which an individual habitually applies a previously successful strategy when a better, more efficient strategy is available, suggests that strategy adoption involves more than simply considering problem and strategy characteristics.

The present study examines the potential role of executive processes in the strategies children choose when solving arithmetic problems. We also examine the contribution of executive processes in children's strategic development in the mathematical domain. No previous models of strategy choice or strategic development implicate executive functions (EFs) in optimal strategy selection, nor do any models assume that age-related changes in executive processes contribute to changes in strategies. Positive findings thus have important theoretical implications regarding strategy selection and strategic development.

2. Age-related differences in EFs

EFs are 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 behaviour. Core EFs include (a) inhibitory control (resisting habits, temptations, or distractions), (b) working memory (mentally holding and processing information), and (c) cognitive flexibility (adjusting to change) (Diamond, 2006; Diamond, Barnett, Thomas, & Munro, 2007; Eslinger, 1996; Jurado & Rosselli, 2007; Lezak, 1995; Logan, 2000; Miyake et al., 2000; Norman & Shallice, 1986; Rabbit, 1997; Stuss & Benson, 1986).

EFs in adults and age-related changes in EFs in children have been investigated using several procedures. In the approach used here, EFs are investigated via neuropsychological tests thought to engage executive functions (Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Lezak, 1995; Spreen & Strauss, 1998). Such tests include the Trail Making Test, Stroop test, and Excluded Letter Fluency Tests. Children’s performance on these tests improves with age (Carlson, 2005; Carlson, Davis, & Leach, 2005;

3. Mathematical performance and EFs

Evidence is mixed regarding a relation between age-related changes in EFs and development of mathematical skills. Age-related changes in EFs are critical to age-related changes in mathematics among preschool children (Bull, 2008; Espy et al., 2004). However, evidence is mixed for elementary-school children (Imbo & Vandierendonck, 2007; Mckenzie, Bull, & Gray, 2003). Imbo and Vandierendonck (2007) investigated the role of executive working memory in age-related changes in arithmetic problem solving. Using a dual-task method, they compared the arithmetic strategies of fourth, fifth, and sixth graders solving simple one-digit arithmetic problems under “load” and “no-load” conditions. In the no-load condition, children performed only the arithmetic problem-solving task. In the load condition, children were asked to categorize randomly displayed sounds into “high” and “low” tones while solving arithmetic problems. The researchers found no interactions between age and working-memory load. Indeed, the effect of working-memory load on strategy selection was identical across age groups. In both conditions, all children used the easier retrieval strategy similarly frequently. Further, age did not interact with working-memory load in affecting strategy execution (i.e., mean performance for each strategy). These findings suggest that the executive components of working memory may not affect developmental changes in children's strategy selection and execution, at least in this age range (McLean & Hitch, 1999). Note, however, that the researchers did not introduce different levels of load (only a “load” and “no-load” condition); if the load factor had been more powerfully manipulated, significant effects may have occurred. Neuropsychological test data suggest that EFs influence children's mathematical performance and strategies (Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Geary et al., 1991; Mckenzie et al., 2003). For example, Bull and Scerif (2001) found that 7-year-old's arithmetic performance correlated significantly with cognitive flexibility (as measured by the Wisconsin Card Sorting Task), even after controlling for reading ability and IQ. Geary et al. (1991) found a working-memory span advantage for normally achieving children, with more errors committed by children with low memory spans. Barrouillet and Lépine (2005) found a significant positive correlation between mean percent use of retrieval strategy in simple arithmetic and measures of working-memory span in both third- and fourth-grade children. Children with high memory spans tended to use retrieval more often than children with low memory spans.

Previous research revealing influence of executive functions on children's arithmetic performance has been limited in several respects. We know that EFs affects children's arithmetic performance and strategies, but we do not know if they affect mathematical and strategic development, and, if they do, what the underlying change mechanisms are. Documenting causal relations stands to provide insight into the shared ontogenetic organization of EFs and mathematical skills and their interaction during cognitive development.

Most important, researchers have not investigated this influence during the school years. Because the link between development of EFs and development of mathematical skills and strategies has been investigated much more extensively in younger than in older children, we know that EFs are related to emergence and early development of mathematical abilities (Bull & Scerif, 2001; Espy et al., 2004; Gathercole & Pickering, 2000; McLean & Hitch, 1999), but we do not know if they are related during late elementary school and early secondary school, when children receive formal mathematical instruction and EFs undergo important changes.

Finally, previous studies have focused on working memory or inhibition, two core EFs. However, Geary et al. (1991) hypothesize that cognitive flexibility, another core EF, might be as important as – if not more important than – other EFs. The correlation between 7-year-olds' cognitive flexibility and their arithmetic performance, reported by Bull and Scerif (2001), is consistent with this possibility. Moreover, proficient arithmetic performance involves alternating strategies on a trial-by-trial basis, which most likely requires cognitive flexibility.
4. The present study

This study examines whether the ability to select the best strategy on a given problem and age-related changes in this ability are related to the development of EFs. We pursued this goal in the domain of arithmetic, but the findings potentially generalize to other cognitive domains.

We tested children’s performance in an under-investigated arithmetic activity, computational estimation. In computational estimation tasks, participants must approximate sums (or products) for problems like 36 + 78 or 36 \times 78. Children of different ages use several types of strategies and improve at finding the best estimate for each problem. Also, in other arithmetic domains, children’s performance is influenced by the types of strategies they use and the types of problems they solve (Baroody, 1989; Case & Sowder, 1990; Dowker, 1997; Dowker, Flood, Griffiths, Harriss, & Hook, 1996; LeFevre, Greenham, & Waheed, 1993; Lemaire & Lecacheur, 2002; Lemaire, Lecacheur, & Farioli, 2000; Levine, 1982; Reys, Rybolt, Bestgen, & Wyatt, 1982; Sowder & Markovits, 1990). Further, as in other arithmetic domains, it is unknown how skill at selecting the best strategy for a given problem changes with age or whether EFs mediate age-related changes.

We asked third, fifth, and seventh graders to select the best estimation strategy for two-digit addition problems, such as 36 + 78. Children could choose rounding-down (i.e., rounding both operands down to the closest smaller decades, using 40 + 60 to solve 42 + 67) or rounding-up strategies (i.e., rounding both operands up to the closest larger decades, using 50 + 70 to solve 42 + 67). These strategies are known and spontaneously used by children as young as seven years old (LeFevre et al., 1993; Lemaire & Lecacheur, 2002; Lemaire et al., 2000). Two types of problems were tested, “homogeneous” problems (i.e., those with unit digits of both operands either smaller or larger than 5 as in 43 + 62 or in 37 + 59) or “heterogeneous” problems (i.e., unit digit of one operand smaller than 5 and unit digit of the other larger than 5, as in 43 + 68), as previous studies of computational estimation showed that size of unit digits influences children's strategies and performance. Mixed-rounding strategy (i.e., rounding one operand down and the other up to the closest decades) was not allowed, because we wished to increase difficulty of strategy selection and thereby maximize age-related differences in mean percent use of the best strategy. Thus, we intentionally avoided allowing children to systematically choose the rounding-down strategy on homogeneous, small-unit problems (e.g., 31 + 82), the rounding-up strategy on homogeneous, large-unit problems (e.g., 27 + 78), and the mixed-rounding strategy on heterogeneous problems (e.g., 28 + 74), which children as young as seven can do. We were primarily interested in assessing strategy selection (i.e., mean percent use of the best strategy for each problem) to identify the relations between EFs and strategy selection and age-related differences in strategy selection. We also analyzed performance in terms of mean solution latencies and mean percent deviation between estimates and exact sums.

EF data were collected for each participant using neuropsychological tests. We assessed three specific EFs: inhibition (Stroop test; Stroop, 1935), cognitive flexibility (Trail Making Test; Partington, 1949), and task monitoring (Excluded Letter Fluency Test; Bryan, Luszcz, & Crawford, 1997). These tests are considered to be valid measures of executive functions (Jurado & Rosselli, 2007; Lezak, 1995; Miyake et al., 2000; Spreen & Strauss, 1998). We examined whether EFs, generally, or some of these EFs specifically influence strategy selection and its development. Inhibition processes and cognitive flexibility were assessed, as they were assumed a priori to be crucial for trial-to-trial changes in strategy selection. Alternating, between strategies entails inhibiting the previously executed strategy and activating a new one. Moreover, we tested task monitoring processes as the repertoire of strategies to select among on each problem was restricted to two strategies. Indeed, when selecting a different strategy on each problem, children had to be careful to choose among the strategies available for this experiment and not among all computational estimation strategies that they knew.

We analyzed our data with three goals in mind. First, we analyzed age-related differences in computational estimation performance in order to compare our results with previous findings (LeFevre et al., 1993; Lemaire & Lecacheur, 2002; Lemaire et al., 2000). As in previous work, we expected performance to improve (i.e., faster solution latencies and higher levels of accuracy) with age. We also expected better performance on the easier, rounding-down strategy than on the rounding-up strategy, and better performance on the easier homogeneous problems than on the heterogeneous problems.

Age-related differences were expected to be larger on the more difficult rounding-up strategy and heterogeneous problems.

Second, we examined whether strategy selection were related to EFs, such that individuals with more efficient EFs would more frequently select the best strategy on each problem. We tested this prediction by examining correlations between measures of EFs and mean percent use of the best strategy with and without age partialed out.

Third, and most important, we examined whether strategic development is mediated by age-related changes in EFs, using hierarchical regression analyses that reveal age-related variance before and after controlling for variance in EFs. We predicted that the proportion of age-related variance in strategy selection would be attenuated when age-related changes in EFs were statistically controlled. Of interest was which EFs measure(s) partially mediate age-related differences in strategy selection for each problem. Thus, we conducted mediational analyses with EFs as a single composite measure as well as analyses for each of the EFs separately.

5. Method

5.1. Participants

Thirty-nine seventh graders (22 females), 36 fourth graders (19 females), and 31 second graders (17 females) participated. Participants' characteristics appear in Table 1. Children were from a French upper-class urban public school.

5.2. Procedure

All individuals participated in two sessions, separated by 1 week. Participants completed the computational estimation task during the first session and the neuropsychological tests of executive functions during the second session.

5.2.1. Computational estimation task

Items were 100 two-digit addition problems (e.g., 54 + 29). Based on the size of unit digits, half of the problems were categorized as homogeneous and half as heterogeneous. Unit digits of both operands were smaller than 5 in half the homogeneous problems (e.g., 42 + 31) and larger than 5 in the other homogeneous problems (e.g., 37 + 28). The unit digit was larger than 5 in the first operand and smaller than 5 in the second operand for half the heterogeneous problems (e.g., 48 + 23), and the reverse was true for the other half (e.g., 43 + 28).

Homogeneous and heterogeneous problems were matched on three factors: the side of the larger operand, mean correct sums, and mean percent deviations. The larger operand was on the left side (e.g., 67 + 26) in half of the problems and on the right side (e.g., 18 + 73) in the others. Mean correct sums were 68 for both types of problems (range 44–86 for homogeneous problems and 42–82 for heterogeneous problems). Finally, for each homogeneous and heterogeneous problem estimated with rounding-down and rounding-up strategies, percent deviations were calculated by dividing the

Table 1

<table>
<thead>
<tr>
<th>Characteristics of participants.</th>
<th>Third graders (N = 31)</th>
<th>Fifth graders (N = 36)</th>
<th>Seventh graders (N = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (range)</td>
<td>8-6 (8-0–9-1)</td>
<td>10-6 (10-2–11-2)</td>
<td>12-6 (12-1–13-2)</td>
</tr>
<tr>
<td>Arithmetic fluency</td>
<td>25.3</td>
<td>39.3</td>
<td>45.1</td>
</tr>
<tr>
<td>Stroop</td>
<td>2.04</td>
<td>1.93</td>
<td>1.40</td>
</tr>
<tr>
<td>ELFT</td>
<td>1.25</td>
<td>.65</td>
<td>.36</td>
</tr>
<tr>
<td>TMT</td>
<td>75</td>
<td>64</td>
<td>42</td>
</tr>
</tbody>
</table>

Note – arithmetic fluency: mean number of correctly solved problems (max = 60) in 6 s (independent paper-and-pencil test). Stroop Test: interference score (i.e., time for the color-incongruent subtest – time for the color-congruent subtest). ELFT (Excluded Letter Fluency Test): i.e., sum of (number of incorrect words divided by number of correct words) for letters A and E. TMT (Trail Making Test): time at TMT B – time at TMT A (in s).
difference between estimate and correct sum by the correct sum, then multiplying by 100. (For example, percent deviations were 10.3% and 15.4% for 41 + 37 when rounding down and rounding up, respectively, and 16.7% and 11.1% for 48 + 24 when rounding down and rounding up, respectively.) Mean percent deviation between correct sums and estimates for homogeneous problems was 15.0% (range 4.1–31.8%) and 15.2% (range 3.9–30.4%) for rounding-down and rounding-up strategies, respectively. Similarly, mean percent deviation between correct sums and estimates for heterogeneous problems was 15.2% (range 9.1–30.2%) and 15.1% (range 9.8–25.0%) for rounding-down and rounding-up strategies, respectively. We matched percent deviations because having one strategy with mean percent deviations smaller on average than those of a second strategy might artifactually lead participants to use the former more often. When one strategy was best for a given problem, the estimated product was closer to the correct product by 10.1% on average (range 3.9–19.1%) compared to the estimate produced by the other strategy. The rounding-down strategy yielded the more accurate sum for half the problems, and the rounding-up strategy yielded the more accurate sum for the others.

Finally, based on previous research (Campbell, 2005; Geary, 1994), problems were selected with the following constraints: (a) no operand had 0 or 5 as unit digits; (b) digits were not repeated in the same unit or decade positions across operands (e.g., 64 + 24); (c) no digits were repeated within operands (e.g., 66 + 31); and (d) no reverse orders of operands were used (e.g., 47 + 32 was used, 32 + 47 was not).

The computational estimation task was defined to participants as giving an approximate answer to an arithmetic problem as close as possible to the correct answer without actually calculating the correct answer. They were further told, “For example, if I have to estimate 28 + 41, I can do 20 + 40 and give 60 as an approximate solution to the problem. I can also do 30 + 50, or do anything else that yields an approximate answer. You are going to see four sets of 25 two-digit addition problems each, with a break in between. Your task is to tell me an approximate sum for each problem. To estimate the sums, you can use either a rounding-up or rounding-down strategy, and no other strategies. Rounding down means that you round each operand down to the closest smaller decades, like when you do 20 × 40 to estimate 26 × 42. Rounding up means that you round each operand up to the closest larger decades, for example when you do 30 × 50 to estimate 26 × 42. For each problem, I want you to try to find the best strategy that will give you the most exact sum. The most exact sum is the one that is the closest to the exact sum. (This was illustrated with examples.) However, be careful. Because I do not want you to give me the exact sum but an approximate sum; you will not have time to calculate exact sums, as your estimates should be stated very quickly.” Participants were further instructed to perform only the initial rounding up or down and nothing more. (That is, they were not to add or subtract amounts after calculating the sum of rounded operands.)

Following a practice period involving 10 problems, no participant displayed any difficulty with either rounding-down or rounding-up strategies. At the beginning of the practice trials, some participants wished to use a mixed-rounding strategy (rounding one operand down to the closest smaller decade and rounding the other operand up to the closest larger decade). After a few practice problems, all participants understood that this strategy was not allowed. At the end of the practice period, all children understood the instructions.

Experimental problems were presented in 72-point Arial font (black color) in the center of a 14-inch computer screen controlled by a Dell Latitude 120L PC. Each trial began with a one-second ready signal (the French word “prêt,” meaning “ready” in English) appearing in the center of the screen. Then, an addition problem was displayed horizontally, with addition symbol and numbers separated by spaces equal to the width of one character. Timing of each trial began when a problem appeared on the screen and ended when the experimenter pressed the space bar on the computer keyboard immediately after the participant’s response. Participants were asked to calculate aloud so the experimenter could note the strategy used. Presentation was controlled by E-Prime software.

After each response, the participant was asked, “Which of the two strategies did you use, the rounding-down or the rounding-up strategy?” Problems remained on the screen as pilot testing revealed that this made it easier for participants to describe their strategies. The experimenter recorded the participants’ responses. The experimenter’s coding of strategies and verbal responses were in agreement on 100% of trials.
Table 2
Mean percent use of rounding-down and of the best strategy on each problem, mean solution times (in ms) and percent errors.

<table>
<thead>
<tr>
<th>Problem type</th>
<th>Percent use of rounding down</th>
<th>Percent use of the best strategy</th>
<th>Solution times</th>
<th>Percent errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Third graders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td>60</td>
<td>71</td>
<td>9153</td>
<td>7.2</td>
</tr>
<tr>
<td>Heterogeneous</td>
<td>60</td>
<td>59</td>
<td>9363</td>
<td>6.4</td>
</tr>
<tr>
<td>Means</td>
<td>60</td>
<td>65</td>
<td>9258</td>
<td>6.8</td>
</tr>
<tr>
<td>Fifth graders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td>53</td>
<td>87</td>
<td>7118</td>
<td>7.9</td>
</tr>
<tr>
<td>Heterogeneous</td>
<td>50</td>
<td>64</td>
<td>7919</td>
<td>5.7</td>
</tr>
<tr>
<td>Means</td>
<td>51</td>
<td>75</td>
<td>7519</td>
<td>6.8</td>
</tr>
<tr>
<td>Seventh graders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homogeneous</td>
<td>53</td>
<td>93</td>
<td>5319</td>
<td>6.1</td>
</tr>
<tr>
<td>Heterogeneous</td>
<td>46</td>
<td>67</td>
<td>6028</td>
<td>5.4</td>
</tr>
<tr>
<td>Means</td>
<td>50</td>
<td>80</td>
<td>5674</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Order of problem presentation was randomized across participants. Each participant was permitted a 5–10-min rest between blocks of 25 problems. Participants took from 30 to 60 min to complete the computational task.

5.2.2. Neuropsychological assessment of executive functions

All participants were first administered the Stroop test, then the Excluded Letter Fluency Test (ELFT), and finally the Trail Making Test (TMT). A female research assistant, not informed of the purpose of the study, tested all participants.

We used two subtests of the standard Stroop Color task (Stroop, 1935): the color-congruent and the color-incongruent subtests. In both versions, 50 color names appeared on a sheet of paper. For each item, color name and color of ink matched (e.g., the word RED printed in red) in the color-congruent subtest and differed (e.g., the word RED printed in blue) in the color-incongruent subtest. In each subtest, participants were asked to name the color of the printed words as quickly as possible, ignoring what the words actually said. If they made a mistake, they were asked to name the color again. For each participant, elapsed time for the color-congruent subtest was subtracted from elapsed time for the color-incongruent subtest. Performance on this task is thought to involve executive abilities, such as mental tracking, inhibition, and lack of distractibility (Bub, Masson, & Lalonde, 2006).

The ELFT (Bryan et al., 1997) is a verbal fluency test. Participants must produce as many words as possible not containing the letter E in the first trial and not containing the letter A in the second trial. For each trial, number of incorrect words was divided by number of correct words, and the sum of ELFT-E and ELFT-A was calculated.

The Trail Making Test (Reitan, 1992), assessing cognitive flexibility, consisted of two parts. In each part, participants viewed 25 circles distributed over a sheet of paper. In Part A, the circles are numbered 1–25, and the participant must draw lines connecting the numbers in ascending order. In Part B, the circles include both numbers (1–13) and letters (A–L). Participants must draw lines connecting the circles by alternating between numbers and letters in ascending order (i.e., 1-A-2-B-3-C, etc.). Participants were to connect the circles as quickly as possible without lifting pen or pencil from the paper. We measured the difference between times taken to execute Part A and Part B.

6. Results

6.1. Age differences in performance

Mean solution times and percent errors (Table 2) were analyzed using a 3 (group: seventh, fifth, and third graders) × 2 (strategy: rounding down, rounding up) × 2 (problem type: homogeneous, heterogeneous problems) mixed-design analysis of variance (ANOVA), with age as a between-subject factor. Seventh graders were faster than fifth graders, who were faster than third graders, F(2,103) = 18.13, p < .05, ηp² = .26. Moreover, participants answered more quickly when solving homogeneous problems...
than when solving homogeneous problems (7770 ms), \( F(1,103) = 53.67, p < .05, \eta^2 = .34 \). This difference was not significant for third graders (210 ms), \( F(1,30) = 1.64 \), but was significant for fifth graders (801 ms), \( F(1,35) = 28.53, p < .05 \), and for seventh graders (709 ms), \( F(1,38) = 58.45, p < .05 \). Analyses of errors revealed that children made few errors (6.4%), and there were no significant main or interaction effects, \( F_s < 1.42 \). (Answers were given a code of “1” if the estimate sum was different from expected given the strategy used and coded “0” otherwise; for example, estimate sums of 72 and 70 for 43 + 38 were coded 1 and 0, respectively.)

6.2. Age differences in strategy use

All participants used both rounding-down and rounding-up strategies. Mean percent use of the rounding-down strategy and mean percent use of the best strategy (Table 2) were analyzed using a 3 (group: seventh, fifth, and third graders) \( \times \) 2 (problem type: homogeneous, heterogeneous problems) mixed-design ANOVA, with age as a between-subject factor. Participants rounded down on 54% of trials and did so more often on homogeneous problems than on heterogeneous problems (55% vs. 52%), \( F(1,103) = 8.98, p < .05, \eta^2 = .08 \). There was a significant main effect of age, \( F(1,103) = 7.97, p < .05, \eta^2 = .13 \). Third graders (60%) rounded down more often than fifth graders (51%), \( F(1,65) = 9.62, p < .05 \), and fifth and seventh graders rounded down equally often, \( F < 1 \). As revealed by the age \( \times \) problem type interaction, \( F(2,103) = 3.22, p < .05, \eta^2 = .04 \), third and fifth graders rounded down equally often on homogeneous and heterogeneous problems. Seventh graders, however, used the rounding-down strategy more often for heterogeneous problems than for homogeneous problems (53% vs. 46%), \( F(1,38) = 11.48, p < .05 \).

Analyses of mean percent use of the best strategy for each problem showed a main effect of age, \( F(2,103) = 11.37, p < .05, \eta^2 = .18 \), and of problem type, \( F(1,103) = 181.25, p < .05, \eta^2 = .64 \). There was also an interaction of age and problem type, \( F(1,103) = 8.29, p < .05, \eta^2 = .14 \). Seventh graders (80%) selected the best strategy on each problem as often as fifth graders (75%), and fifth graders did so more often than third graders (65%), \( F(1,65) = 8.28, p < .05 \). Although all age groups selected the best strategy more often while solving homogeneous problems than while solving heterogeneous problems, this difference was larger for fifth than for third graders (22.2% vs. 11.5%) and larger for seventh than for fifth graders (26% vs. 22%).

6.3. The role of executive functions in age-related differences in strategy selection

We conducted two separate sets of analyses to examine the role of executive functions in age-related differences in strategy selection. The first examined correlations among age, executive functions, and strategy selection to determine whether measures of executive functions correlated with each other and whether some or all correlated with age and mean percent use of the best strategy. A second set of analyses examined potential mediating effects of executive functions on age-related differences, as revealed by contrasts of the magnitude of the age-related variance in strategy selection before and after controlling for executive functions. If statistical control of the executive function measures results in substantial attenuation of the age-related variance in strategy selection, it can be inferred that executive functions likely play a mediating role in the relations between age and strategy selection.

Table 3 shows correlations between mean percent use of the best strategy for each problem and measures of executive functions (with and without age partialed out). Among executive function measures, Stroop and TMT measures correlated significantly with each other; ELFT did not correlate with either Stroop or TMT measures. In this table, we also include one composite measure (EF) of executive functions – the mean of standardized z scores for all three measures of executive function. Mean percent use of the best strategy was correlated with all measures of executive functions and with the composite executive score. Age correlated with all measures of EFs and with mean percent use of best strategy.

To assess mediational effects, we compared the proportion of variance (reflected in increments of \( R^2 \) corresponding to squared semi-partial correlations) associated with age before and after con-

Table 3
Correlations between percentages of use of the best strategy and measures of executive functions.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>% Best</th>
<th>Stroop</th>
<th>ELFT</th>
<th>TMT</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-order correlations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age –</td>
<td>.42*</td>
<td>−.34*</td>
<td>−.35*</td>
<td>−.42*</td>
<td>−.54*</td>
<td></td>
</tr>
<tr>
<td>% Best –</td>
<td></td>
<td>−.35*</td>
<td>−.21*</td>
<td>−.30*</td>
<td>−.42*</td>
<td></td>
</tr>
<tr>
<td>Stroop –</td>
<td></td>
<td>.03</td>
<td>.43*</td>
<td>.70*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELFT –</td>
<td></td>
<td></td>
<td>.19†</td>
<td>.59*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TMT –</td>
<td></td>
<td></td>
<td></td>
<td>.78*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlations with age partialed out</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Best –</td>
<td></td>
<td>−.25*</td>
<td>−.21*</td>
<td>−.24*</td>
<td>−.25*</td>
<td></td>
</tr>
<tr>
<td>Stroop –</td>
<td></td>
<td></td>
<td>−.10</td>
<td>.34*</td>
<td>.66*</td>
<td></td>
</tr>
<tr>
<td>ELFT –</td>
<td></td>
<td></td>
<td></td>
<td>.05</td>
<td>.51*</td>
<td>.73*</td>
</tr>
<tr>
<td>TMT –</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note – % Best: mean percent use of the best strategy. Stroop Test: interference score (i.e., time for the color-incongruent subtest – time for the color-congruent subtest). ELFT (Excluded Letter Fluency Test): i.e., sum of (number of incorrect words divided by number of correct words) for letters A and E. TMT (Trail Making Test): time at TMT B – time at TMT A. EF: mean of z scores for Stroop Test, ELFT, and TMT.

* p < .01.
† p < .06.

7. Discussion

The present results documented age-related differences in children's computational estimation performance and strategies. They replicated previous findings regarding children's computational estimation skills and documented previously unknown aspects of age-related differences in cognitive strategies. As in previous studies investigating children's computational estimation (Baroody, 1989; Case & Sowder, 1990; Dowker, 1997; Dowker et al., 1996; LeFevre et al., 1993; Lemaire & Lecacheur, 2002; Lemaire et al., 2000; Levine, 1982; Reys et al., 1982; Sowder & Markovits, 1990), the present study showed an overall, age-related increase in accuracy and speed in estimating answers to two-digit addition problems. This age-related improvement was found for both the rounding-up and rounding-down strategies. Children were faster and more accurate with the rounding-down strategy in all three grades. Moreover, problem type mattered for at least the older children, as fifth and seventh graders performed better while solving homogeneous problems than heterogeneous ones; third graders, by contrast, solved these two types of problems equally well. As in all arithmetic activities, children's
performance was influenced by the types of strategies they used and the types of problems they solved.

The present study revealed age-related differences in strategy use, both in terms of the relative frequencies with which each age group used each rounding strategy and in terms of how often children selected the best strategy. Third graders used the rounding-down strategy more often than the other two age groups and more often than the rounding-up strategy. Fifth and seventh graders used the rounding-down strategy equally often and as frequently as the rounding-up strategy.

Most important, this study revealed that (a) children’s skill at selecting the best strategy for each problem improves with age, and (b) increased efficiency in EFs contributes significantly to age-related improvement in children’s strategy selection skills. With age, children were increasingly able to select the best strategy for each problem. Mean percent use of the best strategy increased from 60% in third graders to 75% in fifth graders to 80% in seventh graders. Thus, the difference in strategy selection efficiency was greater between third and fifth graders than between fifth and seventh graders, but seventh graders did show some improvement. Age-related improvement in strategy selection was larger for homogeneous than for heterogeneous problems. These findings are consistent with previous research using computational estimation and other arithmetic problem solving tasks (Siegler, 1996).

Our results reveal significant correlations between executive functions and mean percent use of the best strategy for each problem. This result extends previous findings that children scoring higher for some executive functions (e.g., working memory span) show better arithmetic performance and may be better able to select the most efficient arithmetic strategy on a given problem (Barrouillet & Lépine, 2005; Bull et al., 1999; Geary et al., 1991; Noel, 2009). Our results show that two additional executive functions, inhibition processes and cognitive flexibility, are related to strategy selection and to age-related differences in strategy selection. Regarding the nature of these relationships – specifically, how EFs might affect strategy selection and/or age-related differences in strategy selection – our data are correlational, not causal. Future research should directly examine potentially causal relationships. Several research strategies might be adopted to achieve this end. For example, one might identify an experimental effect of EFs and determine whether the magnitude of this effect changes with participants’ age. Strategy switch costs – effects found by Lemaire and Lecacheur (2010) and Luwel et al. (2009) in adults – may work well toward this end. For example, Lemaire and Lecacheur (2010) found that young adults perform more poorly when they use two different strategies for two consecutive problems than when they repeat the same strategy; they also tend to repeat a strategy over two consecutive problems rather than use two different ones. Finding that strategy switch costs decrease with age would support the hypothesis that age-related increased efficiency in EFs fosters growth in children’s strategy selections.

Currently, we can only speculate about the mechanisms by means of which EFs might affect strategy selection and how age-related increased efficiency of EFs might lead to better strategy selection. First, cognitive flexibility may play a key role in how EFs affect strategy selection. Cognitive flexibility typically refers to the ability to switch from one mental entity (representation or strategy) to another across trials (Chevalier & Blaye, 2008; Crag & Chevalier, 2010). This entails inhibiting a previously relevant (but currently irrelevant) mental entity and activating a now relevant mental entity. Specifically, to choose the best strategy on a given trial, one must inhibit a previously executed strategy and activate a new (or sometimes the same) strategy. More efficient inhibitory processes and age-related improvement in cognitive flexibility may help children more easily switch strategies on a trial-by-trial basis – and even more so as they grow older. Such mechanisms are plausible in the domain of arithmetic strategy selection; however, they may not be specific to the case of arithmetic. Such mechanisms have already been proposed for other cognitive domains such as scientific reasoning (Kuhn & Pease, 2009) or categorization (Blaye, Chevalier, & Paour, 2007), and they may be worth examining in other cognitive domains where strategic variations are correlated with age-related improvement in children’s performance, such as memory, decision making, reading, writing, and attention (Siegler, 1996).

Our findings indicate that executive functions contribute to strategy selection, suggesting that models of strategy choice should include EFs as determiners. Several formal models of strategy choice have been proposed, including Lovett and Anderson’s 1996 ACT-R model, Lovett and Schunn’s 1999 RCCL model, Payne, Bettman, and Johnson’s 1993 adaptive decision maker model, Rieskamp and Otto’s
2006 SSL model, and Siegler and Arraya's 2005 SCADS* model. These models share core assumptions regarding strategy selection processes. For example, choosing among multiple strategies crucially involves associative mechanisms such as assessing relative costs/benefits of each strategy and selecting the one that works best for a given problem on the basis of problem and strategy characteristics.

None of the models of strategy choice propose that strategy selection involves EFs; nor do any assume that age-related changes in EFs influence development of strategy selection. Correlations we found between EF measures and percent use of the best strategy on each problem, and the decrease of proportion of age-related variance after control of EFs, suggest that these models could profitably be extended. Additional assumptions may explain how EFs influence strategy choices and may computationally specify how developing EFs influence strategic development in children.

References


