The development of strategy use in elementary-school children: Working memory and individual differences

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Abstract

The present study tested the development of working-memory involvement in children's arithmetic strategy selection and strategy efficiency. To this end, an experiment – in which the dual-task method and the choice/no-choice method were combined – was administered to 10-, 11-, and 12-year-old children. Working memory was needed in retrieval, transformation, and counting strategies, but the ratio between available working-memory resources and arithmetic task demands changed across age. More frequent retrieval use, more efficient memory retrieval, and more efficient counting processes reduced the working-memory requirements. Strategy efficiency and strategy selection were also modified by individual differences such as processing speed, arithmetic skill, gender, and math anxiety. Short-term memory capacity, on the other hand, was not related to children's strategy selection or strategy efficiency.

Key words: mental arithmetic, strategy, working memory, central executive, digit span, processing speed, math anxiety, gender

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Learning to perform simple-arithmetic tasks efficiently and without much effort is one of the most fundamental skills taught during the elementary-school years. Several cognitive mechanisms may underpin the development of arithmetic skill in children. The present study was designed to investigate the role of one such a cognitive mechanism, namely the executive component of working memory. Besides an on-line study of the role of working memory in the development of children's arithmetic strategy use, we also tested the influence of individual-difference variables such as processing speed, short-term memory, arithmetic skill, math anxiety, and gender.

The role of working memory in children's arithmetic strategy use

Working memory can be defined as a set of processing resources of limited capacity, involved in information maintenance and processing (e.g., Baddeley & Logie, 1999; Engle, Tuholski, Lauglin, & Conway, 1999; Miyake, 2001). Most researchers agree that working-memory resources play a role in children's simple-arithmetic performance. This assertion is mainly based on studies showing a working-memory deficit in mathematically disabled children (e.g., Bull, Johnston, & Roy, 1999; Geary, Hoard, & Hamson, 1999; McLean & Hitch, 1999; Passolungi, Cornoldi, & De Liberto, 1999; Passolunghi & Siegel, 2004; Swanson & Beebe-Frankenberger, 2004; Swanson & Sachse-Lee, 2001; van der Sluis, de Jong, & van der Leij, 2004). The goal of our study, however, was to investigate the role of working memory in arithmetic strategy use in normally developing children. To this end, we had to overcome several shortcomings of the studies mentioned above, which will be discussed below.

First, the role of working memory has predominantly been studied by means of *correlations* between working-memory measures (e.g., counting span, Trails task, Stroop task) and simple-arithmetic performance (e.g., Bull & Scerif, 2001; Bull & Johnston, 1997; Bull, Johnston, & Roy, 1999; McLean & Hitch, 1999; Passolunghi & Siegel, 2001). As correlation is not causation, it is still possible that working-memory measures and mathematical ability rely on a common factor such as general intelligence or processing speed.

In the present study, we aimed at investigating the role of working memory in children's arithmetic performances *on-line*. To this end, the dual-task method was used, in which children have to solve simple-arithmetic problems (i.e., the primary task) while their working memory was loaded by means of the secondary task. The dual-task method has frequently been used in adult studies (see DeStefano & LeFevre, 2004, for a review), which clearly showed that working memory is needed in adults' simple-arithmetic performance. More specifically, adult's simple-arithmetic performance always relies on *executive* working-memory resources, as opposed to verbal and visuo-spatial working-memory resources, of which the role in simple arithmetic is less clear.

Although the dual-task method has rarely been used in child studies, Hitch, Cundick, Haughey, Pugh, and Wright (1987) conducted a dual-task study in which children had to verify simple addition problems (e.g., 3 + 5 = 7, true/false?) while their memory was phonologically loaded. As errors and latencies rose under such a load, Hitch and colleagues conclude that children's counting processes involve inner speech. The dual-task method was further used by Kaye, deWinstanley, Chen, and Bonnefil (1989). In their study, 2^{nd}, 4^{th}, and 6^{th} graders verified simple addition problems while their working memory was loaded by means of a probe detection task. This secondary task affected addition speed most profoundly in 2nd graders, and much less in 4th and 6th graders, indicating that computational efficiency increases with increasing grade level. Adams and Hitch (1997), finally, did not use the dual-task method but manipulated the presentation format of addition problems (i.e., oral vs. visual presentation). The visual presentation provided an external record of the addends which reduced working-memory load. As children's performance was better in the visual condition than in the oral condition, Adams and Hitch concluded that children's mental-arithmetic performance is mediated by working-memory resources. Unfortunately, none of these studies investigated the impact of an executive working-memory load on children's arithmetic performance.

A second shortcoming in previous studies is the ignorance of the locus of effect of working-memory support. Although it has been shown that working-memory resources correlate with arithmetic performance, it is not clear whether working memory is needed in strategy selection processes (i.e., which strategies are chosen to solve the problem?) and/or strategy efficiency processes (i.e., is the problem solved fast and accurately by means of the chosen strategy?). This is a relevant question though, since children do use several strategies to solve simple-arithmetic problems (e.g., Barrouillet & Lépine, 2005; Davis & Carr, 2002; Geary, 1994; Geary & Brown, 1991; Geary, Brown, & Samaranayake, 1991; Geary et al., 1999; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; Mabbott & Bisanz, 2003; Noël, Seron, & Trovarelli, 2004; Siegler, 1987, 1996; Steel & Funnell, 2001; Svenson & Sjöberg, 1983), such as direct memory retrieval (e.g., 'knowing' that $8 + 5 = 13$), transformation (e.g., $8 + 6 = 8 + 2 + 4 = 10 + 4 = 14$), and counting (e.g., $4 + 3 = 4…5…6…7$).

Unfortunately, all studies mentioned included a choice condition only (i.e., a condition in which the children were free to choose any strategy they wanted). It has been shown convincingly that choice conditions do provide reliable measures of strategy selection, but not of strategy efficiency (Siegler & Lemaire, 1997). Indeed, strategy efficiency measures are biased by the strategy selection process. Because the present study aimed to investigate the role of working memory in both strategy selection and strategy efficiency, the choice/no-choice method (devised by Siegler & Lemaire, 1997) was used. This method does not only include a choice condition, but also several no-choice conditions, in which participants are asked to use one single strategy for all problems. Data obtained in no-choice conditions provide reliable strategy efficiency measures. Some recent studies successfully applied the choice/no-choice method to investigate children's arithmetic performance (e.g., Carr & Davis, 2001; Lemaire & Lecacheur, 2002; Torbeyns, Verschaffel, & Ghesquière, 2002, 2004, 2005).

A third and final shortcoming is that very few studies investigated the role of working memory in normally achieving children (but see Adams & Hitch, 1997; Ashcraft & Fierman, 1982; Bull & Scerif, 2001; Geary, Bow-Thomas, Liu, & Siegler, 1996; Hecht, Torgesen, Wagner, & Rashotte, 2001; Kaye et al., 1989). As we believe it is important to know how the interaction between working memory and arithmetic performance progresses in a normal development, the present study tested children without mathematical disabilities. A similar research question was raised by Barrouillet and Lépine (2005), who tested normally developing elementary-school children. They observed that children with high working memory capacities solved simple-addition problems more efficiently than children with low working-memory capacities. Working-memory capacity correlated with strategy selection as well: percentages retrieval use were higher in high-capacity children than in low-capacity children.

To summarize, the present study addresses the development of working-memory involvement in children's arithmetic strategy use. To this end, an experiment combining the dual-task method and the choice/no-choice method was administered to 10-, 11-, and 12-year-old children. The dual-task method permits an on-line investigation of working-memory involvement in arithmetic performance, and the choice/no-choice method permits collection of reliable strategy selection and strategy efficiency data. The combination of both methods has been successfully used in adult studies (Imbo & Vandierendonck, unpublished results) but not yet in child studies. However, results obtained in adult studies cannot simply be generalized to children. Therefore, the present study did not only investigate the development of working-memory involvement in children's strategies; it also tested whether or not results obtained in adult studies apply for children.

Our hypotheses are based on the assertion that many working-memory resources are needed during the initial phase of learning and that fewer working-memory resources are needed as procedural strategies (transformation and counting) are used less frequently and arithmetic facts become represented in long-term memory (see also Ackerman, 1988, Geary et al., 2004; Siegler, 1996). We suppose, however, that the decrease of working-memory involvement in arithmetic tasks across development is not caused by strategy selection processes only, but also by strategy efficiency processes.

First, age-related differences in *strategy selection* might change the ratio between working-memory involvement and the demands of the arithmetic task. As direct memory retrieval needs fewer working-memory resources than non-retrieval strategies, a more frequent retrieval use might reduce the requirements of the arithmetic task, leaving more working-memory resources free for the secondary task. Otherwise stated, the impact of a working-memory load on the arithmetic task will diminish when strategy selection becomes more efficient (i.e., when the outcome of the selection process leads to the least demanding strategy).

The ratio between working-memory involvement and simple-arithmetic task demands might further be changed by more efficient *retrieval* use. As direct memory retrieval relies on working-memory resources (Imbo & Vandierendonck, unpublished results), it is hypothesized that faster retrieval would need fewer working-memory resources than slow and effortful retrieval. Indeed, as problem-answer associations become stronger across development, fewer working-memory resources would be needed to retrieve the correct solution form long-term memory.

Third, we hypothesized that an age-related increase in *non-retrieval* strategy efficiency would also change working-memory involvement. As non-retrieval strategies (transformation and counting) rely heavily on working-memory resources (Imbo & Vandierendonck, unpublished results), it is hypothesized that more efficient procedural use would need fewer working-memory resources than less efficient procedural use. The componential steps used in non-retrieval strategies would become more practiced and require less effort with age, resulting in lower working-memory demands. The latter two hypotheses imply an age-related decrease in the impact of working-memory load on strategy efficiency. More specifically, we anticipate that the execution time of retrieval, transformation, and counting strategies will suffer less from a working-memory load as children become older.

Finally, we expected an age-related decrease in the working-memory costs due to general (i.e., non-mathematical) processes such as encoding stimuli and pronouncing answers. To test this prediction, a 'naming' condition was included in the present study. In this condition, children had to name the correct answer to the problem presented on the screen. It was expected that the naming task would require fewer working-memory resources with growing age. The naming condition also offers the opportunity to test whether direct memory retrieval relies on working memory. If the impact of working-memory load on retrieval is larger than on naming, one may conclude that the very specific fact retrieval processes (i.e., long-term memory access, activation of the correct answer, and inhibition of incorrect answers) need working-memory resources.

Individual differences in children's arithmetic strategy use

To enhance understanding of children's arithmetic strategy use, the present study tested individual differences as well. Five individual-difference variables that might influence children's arithmetic performance were selected: short-term memory, processing speed, arithmetic skill, math anxiety, and gender.

Short-term memory. Short-term memory is a system that passively stores information and can be distinguished from working memory (which entails both storage and processing) already from 7 years of age on (Kail & Hall, 2001). Although the relation between short-term memory and arithmetic ability in mathematically disabled children is still questioned, short-term memory is not expected to play a great role in normally achieving children's arithmetic ability. Bull and Johnston (1997), for example, observed no correlations between short-term memory and retrieval frequency, retrieval efficiency, or counting efficiency. In the present study, the digit span was used in order to collect data on the short-term capacity of the children.

Processing speed. The relationship between processing speed and arithmetic ability was first examined by Bull and Johnston (1997). These authors observed that processing speed was – among several other variables such as short-term memory, speech rate, and item identification – the best predictor of mathematical ability. This result was further confirmed by Kail and Hall (1999), who observed that processing speed had the strongest and most consistent relation to arithmetic problem solving. Hitch, Towse, and Hutton (2001), however, maintain that working-memory span is a better predictor of arithmetic ability than processing speed. In a longitudinal study by Noël et al. (2004), processing speed did not predict children's later performance on addition tasks. They observed, however, a bizarre correlation between processing speed and retrieval frequency: slower subjects were those who used retrieval more frequently. Whether or not processing speed is a critical determinant of simple-arithmetic performance thus stays very equivocal. As efficient strategy execution is generally defined as fast (and correct) strategy execution, we expected a positive correlation between processing speed and strategy efficiency. Because efficiently executed strategies strengthen the problem-answer association in long-term memory, we further expected that children with a higher processing speed would use retrieval more frequently. This expectation is in disagreement with the observation of Noël et al. (2004) but is intuitively more compelling than expecting a negative correlation between processing speed and retrieval frequency.

Arithmetic skill. The relation between arithmetic skill on the one hand and strategy selection and strategy efficiency on the other hand is straightforward: persons who frequently use retrieval and who are fast in executing strategies will perform better on arithmetic skill tests. This relation has been shown in adults (e.g., Ashcraft, Donley, Halas, & Vakali, 1992; Campbell & Xue, 2001; Kirk & Ashcraft, 2001; Hecht, 1999; Imbo, Vandierendonck, & Rosseel, in press; LeFevre et al., 1996a, 1996b) and in children (e.g., Geary & Burlingham-Dubree, 1989). We expected more frequent retrieval use and more efficient strategy use in high-skill children than in low-skill children.

Math anxiety. In adults, math anxiety is an individual-difference variable that affects on-line performance in math-related tasks (Ashcraft & Kirk, 2001). High and low-anxious adults have been shown to differ especially in complex-arithmetic tasks (e.g., sums of two 2-digit numbers) but not in simple-arithmetic tasks (Ashcraft, 1995; Ashcraft & Faust, 1994; Faust, Ashcraft, & Fleck, 1996). More recently however, effects of math anxiety have been observed on simple-arithmetic strategy use in adults (Imbo & Vandierendonck, unpublished results). Generally, high-anxious adults were slower in the execution of both retrieval and non-retrieval strategies. Effects of math anxiety on strategy selection were also found: percentage retrieval use was lower in high-anxious adults than in low-anxious adults. In the present child sample, high-anxious children were expected to be less efficient than low-anxious children, and high-anxious children were expected to use retrieval less often than low-anxious children.

Gender. Several studies indicated that gender differences exist in arithmetic strategy choices made by elementary-school children. More specifically, direct memory retrieval would be chosen more frequently by boys whereas non-retrieval strategies would be chosen more frequently by girls (Carr, 1996; Carr & Jessup, 1997; Davis & Carr, 2002). With respect to strategy efficiency, gender differences exist as well: boys are faster than girls in executing computational processes (Carr & Jessup, 1997; Carr, Jessup, & Fuller, 1999; Fennema, Carpenter, Jacobs, Franke, & Levi, 1998; Geary, Bow-Thomas, Fan, & Siegler, 1993; Geary, Hamson, & Hoard, 2000) and more specifically in direct memory retrieval (Royer, Tronsky, Chan, Jackson, & Marchant, 1999). Based on these previous results, we expected more frequent and more efficient retrieval use in boys than in girls.

Method

Participants

Sixty-three children participated in the present study. They all attended the same elementary school in the Flemish part of Belgium. Twenty-one of them were in the 4th grade of elementary school (mean age: 10 years 0 months; 9 girls and 12 boys), twenty-one other children were in the 5th grade of elementary school (mean age: 11 years 1 month; 10 girls and 11 boys), and the last twenty-one children were in the 6th grade of elementary school (mean age: 12 years 2 months; 14 girls and 7 boys). The children were selected from the whole ability range, although those who were considered by their teachers to have specific learning or behavioral difficulties were excluded. The children had no documented brain injury or behavioral problems. The children only participated when they, as well as their teachers and their parents consented.

Procedure

Several individual-difference tests and one dual-task experiment were administered to each child. The whole procedure (individual-difference tests and dual-task experiment) took about one hour per child, but was divided into two parts of 30 minutes each. Each child was tested individually in a quiet room. It started with short questions about the child such as age, grade (4^{th}, 5^{th}, or 6^{th}), and math anxiety (on a rating scale from 1 “low” to 5 “high”). Then, the first part of the dual-task experiment was run, after which the digit span test was administered. About five days later, the second part of the dual-task experiment was run, after which the processing speed test was administered. Once all individual experiments were run, the arithmetic skill test was run classically. Each individual-difference test and the dual-task experiment (consisting of a primary task and a secondary task) are described more extensively below.

Primary task: solving simple addition problems. The children had to solve simple addition problems in five conditions: a choice condition, three no-choice conditions, the order of which was randomized, and a naming condition, in which correct answers were presented on the screen. The choice condition was always the first in order to exclude influence of no-choice conditions on the choice condition, and the naming condition was always the last one in order to exclude effects of naming on solving the problems. In the choice condition, 6 practice problems and 32 experimental problems were presented. The no-choice conditions immediately started with the 32 experimental problems. Each condition was further divided in two blocks: a control block without working-memory load and a block in which the executive component of working memory was loaded. For half of the children, each condition started with the no-load block and was followed by the working-memory load block, whereas the order was reversed for the other half of the children.

The addition problems were composed of pairs of numbers between 2 and 9 of which the sum exceeded 10 (e.g., 6 + 7). Problems involving 0 or 1 as an operand or answer (e.g., 5 + 0) and tie problems (e.g., 8 + 8) were excluded. Since commuted pairs (e.g., 9 + 4 and 4 + 9) were considered as two different problems, this resulted in 32 addition problems (ranging from 2 + 9 to 9 + 8). A trial started with a fixation point for 500 milliseconds. Then the addition problem was presented horizontally in the center of the screen, with the + sign at the fixation point. In the naming condition, the problem was presented with its correct answer (e.g., "9 + 8 = 17"). The problem remained on screen until the child responded. Timing began when the stimulus appeared and ended when the response triggered the sound-activated relay. To enable this sound-activated relay, children wore a microphone which was activated when they spoke their answer aloud. This microphone was connected to a software clock accurate to 1ms. On each trial, feedback was presented to the children: a happy face when their answer was correct and a sad face when their answer was incorrect.

Immediately after solving each problem, children in the choice condition were presented four strategies on the screen (see e.g., Campbell & Gunter, 2002; Campbell & Xue, 2001; Kirk & Ashcraft, 2001; LeFevre et al., 1996b; Seyler, Kirk, & Ashcraft, 2003): 'Retrieval', 'Count', 'Transform', and 'Other'. These four choices had been extensively explained by the experimenter. Retrieval: You solve the problem by remembering or knowing the answer directly from memory. Count: You solve the problem by counting a certain number of times to get the answer. Transform: You solve the problem by referring to related operations or by deriving the answer from known facts. Other: You solve the problem by a strategy unlisted here, or you do not know what strategy that you used to solve the problem. Examples of each strategy were presented as well. Children had to report verbally which of these strategies they had used.

In the no-choice conditions, children were forced to use one particular strategy to solve all problems. In no-choice/retrieval, they were asked to retrieve the answer, in no-choice/transform, they were asked to transform the problem by making an intermediate step to 10 (e.g., 9 + 6 = 9 + 1 + 5 = 10 + 5 = 15), and in no-choice/count, they had to count (subvocally) until they reached the correct total (e.g., 7 + 4 = 7…8…9…10…11). Children were free to choose whether or not they started to count from the larger addend on (cf. the 'min' counting strategy, Groen & Parkman, 1972). After having solved the problem, children also had to answer with 'yes' or 'no' whether they had succeeded in using the forced strategy. In choice and no-choice conditions, the child's answer, the strategy information, and the validity of the trial were recorded on-line by the experimenter. All invalid trials (e.g., failures of the voice-activated relay) were discarded and returned to at the end of the block, which minimized data-loss due to unwanted failures.

Secondary task: executive working-memory load. An adapted version of the Continuous Choice Reaction Time Task – Random (CRT-R task; Szmalec, Vandierendonck, & Kemps, 2005) was used to load the executive working-memory component. That is to say, we changed the CRT-R task in order to be used in elementary-school children. More specifically, compared to the 'original' version of the CRT-R, the difference between low and high tones was larger (262 and 1048 Hz vs. 262 and 524 Hz); the interval between both tones was longer (2000 and 2500 ms vs. 900 and 1500 ms); and the duration of each tone was longer (300 ms vs. 200 ms). Children had to press the 4 on the numerical keyboard when they heard a high tone and the 1 when a low tone was presented. This task was also performed alone (i.e., without the concurrent solving of addition problems) at the beginning of the working-memory load block.

Digit span. Digit span was tested using the WISC-R digit span subtest (Wechsler, 1986). In this task, digits are read aloud by the experimenter and the child has to repeat these digits in the correct order. There were two trials for each span length. The experimenter started from a span length of two and continued until the child made a mistake in both trials of the same span length. The highest span length reached by the child was set as ‘digit span’.

Processing speed. Processing speed was tested by a visual number matching task (also used by Bull & Johnston, 1997[1]), which comprised 30 rows of 6 digits, with 2 digits in each row being identical (for example 5 3 1 8 9 3). The child was instructed to cross out the identical digits in each row, and to work as quickly and as accurately as possible. The performance measure was the time taken to complete all 30 rows of digits. Note that a higher measure indicates a slower performance.

Arithmetic skill. A standardized skill test (Arithmetic Tempo Test; De Vos, 1992) was administered classically after all individual experiments were run. This pen-and-paper test consists of several subtests that require elementary computations. Each subtest concerns only one arithmetic operation. In the present experiment, the first two subtests were administered, i.e., the addition subtest (e.g., 2 + 3 = ?; 76 + 18 = ?) and the subtraction subtest (7 – 5 = ?; 54 – 37 = ?), each consisting of 40 items of increasing difficulty. The child was given 1 minute for each subtest and had to solve as many problems as possible within that minute. Performance on the test was the sum of the addition and the subtraction subtest.

Results

Of all trials, 5.2% was spoiled due to failures of the sound-activated relay. Since all these invalid trials returned at the end of the block, most of them were recovered from data loss, which reduced the trials due to failures of the sound-activated relay to 0.8%. Further, all incorrect trials (3.5%), all choice trials on which children reported having used a strategy 'Other' (0.3%), and all no-choice trials on which children failed to use the forced strategy (8.8%) were deleted. All data were analyzed on the basis of the multivariate general linear model; and all reported results are considered to be significant if $p < .05$, unless mentioned otherwise.

The results section is subdivided into four parts. We start with the results of the secondary task. Thereafter, the results concerning strategy efficiency and strategy selection are reported. Finally, the importance of individual differences is discussed. Due to voice-key problems, two subjects (one 4^{th} grader and one 6^{th} grader) were excluded from analyses, leaving scores for twenty 4^{th} graders, twenty-one 5^{th} graders, and twenty 6^{th} graders.

Secondary task performance

A 3 x 6 ANOVA was conducted on accuracies of the CRT-R task with Grade (4^{th}, 5^{th}, 6^{th}) as between-subjects factor and Primary task (no primary task, naming, no-choice/retrieval, no-choice/transform, no-choice/count, choice) as within-subjects factors (see Table 1). The main effect of Grade was significant, $F(2,58) = 5.77$, $MS_e = 3770$: 4^{th} graders were less accurate than 5^{th} graders, $F(1,58) = 8.95$ but there was no difference between 5^{th} and 6^{th} graders, $F(1,58) < 1$. The main effect of Primary task was significant as well, $F(5,54) = 16.53$, $MS_e = 270$. Executing the CRT-R task without the primary task was more accurate than CRT-R performance during naming, $F(1,58) = 4.49$, which was in its turn more accurate than CRT-R performance during no-choice/retrieval, $F(1,58) = 53.49$. CRT-R accuracy did not differ between no-choice/retrieval, no-choice/transform, and choice conditions, all $F(1,58) < 1$, but CRT-R accuracy was lower in the latter three conditions than in the no-choice/count condition, $F(1,58) = 10.47$, $F(1,58) = 4.01$, and $F(1,58) = 13.36$, respectively.

A similar 3 x 6 ANOVA was conducted on correct RTs of the CRT-R task (see Table 1). The main effect of Grade did not reach significance, $F(2,58) < 1$, $MS_e = 75586$, but the main effect of Primary task did, $F(5,54) = 25.99$, $MS_e = 36387$. Executing the CRT-R task without the primary task was faster than CRT-R performance during naming, $F(1,58) = 4.50$, which was in its turn faster than CRT-R performance during no-choice/retrieval, $F(1,58) = 24.78$. There were no significant differences in CRT-speed between no-choice retrieval, no-choice transform, no-choice count, and choice conditions, all $F(1,58) < 1$, except one: CRT-R performance was faster in no-choice/count than in no-choice/retrieval, $F(1,58) = 4.24$. The Grade x Primary task interaction was not significant, $F(10,110) < 1$.

Strategy efficiency

As accuracies were very high, (100% in no-choice/naming, 97% in no-choice/retrieval, 98% in no-choice/transform, 98% in no-choice/count, and 95% in choice), strategy efficiency was analyzed in terms of strategy speed. Only the RTs uncontaminated by strategy choices (i.e., no-choice RTs) were considered. A 3 x 2 x 4 ANOVA was conducted on correct RTs with Grade (4^{th}, 5^{th}, 6^{th}) as between-subjects factor and Load (no load vs. load) and Task (naming, retrieval, transformation, counting) as within-subjects factors (see Table 2).

The main effect of Load was significant, $F(1,58) = 83.53$, $MS_e = 221390$, with higher RTs under load than under no-load. The main effect of Grade was also significant, $F(2,58) = 8.17$, $MS_e = 4145150$. Fourth-grade children were significantly slower than 5^{th} grade children, $F(1,58)$

= 9.30, but there was no difference between 5th and 6th grade children, $F(1,58) < 1$. The main effect of Task, finally, was significant as well, $F(3,56) = 104.56$, $MS_e = 1451894$. Naming was faster than retrieval, $F(1,58) = 297.93$, retrieval was faster than transformation, $F(1,58) = 43.02$, and transformation was faster than counting, $F(1,58) = 28.62$.

Task further interacted with Grade, $F(6,114) = 4.08$ and with Load, $F(3,56) = 3.68$. The Task x Grade interaction indicated that the decrease in RTs over grades differed across strategies. Naming RTs decreased from 4th to 5th grade, $F(1,58) = 12.08$ but did not change anymore from 5th to 6th grade, $F(1,58) < 1$. Retrieval RTs, on the other hand, decreased from 4th to 5th grade, $F(1,58) = 5.95$ and from 5th to 6th grade, $F(1,58) = 6.24$. Transformation RTs did not change from 4th to 5th grade, $F(1,58) = 2.10$ or from 5th to 6th grade, $F(1,58) < 1$. Counting RTs, finally, decreased from 4th to 5th grade, $F(1,58) = 11.86$ but not from 5th to 6th grade, $F(1,58) < 1$.

The Task x Load interaction showed that the effect of working-memory load (i.e., RT load – RT no-load) was the largest on transformation RTs (606ms). This effect was larger than on naming RTs (299ms), $F(1,58) = 10.58$, retrieval RTs (375ms), $F(1,58) = 5.39$, and counting RTs (278ms), $F(1,58) = 7.57$. As hypothesized, the effect of load was larger on retrieval RTs than on naming RTs, $t(58) = 1.87$, indicating that the retrieval process requires extra executive working-memory resources. It should be noted, however, that the effect of load was significant in each single task; $F(1,58) = 122.59$ for naming, $F(1,58) = 106.45$ for retrieval, $F(1,58) = 43.73$ for transformation, $F(1,58) = 7.28$ for counting.

The Grade x Load and Grade x Load x Task interactions did not reach significance, $F(2,58) = 1.40$ and $F(6,114) < 1$, respectively. Planned comparisons were conducted, however, to test the development of working-memory involvement in the different strategies. Whereas the effect of load on naming RTs did not change linearly[2] across grades, $F(1,58) = 1.08$, the effect of load on retrieval RTs decreased linearly across grades, $F(1,58) = 4.91$, with load effects of

472ms, 382ms, and 273ms for 4th, 5th, and 6th grade, respectively. The effect of load on transformation RTs did not change either, $F(1,58) < 1$. The effect of load on the counting strategy, finally, tended to decrease linearly, $t(58) = 1.56$ ($p = .062$, one-tailed), with load effects of 479ms, 270ms, and 83ms, for 4th, 5th, and 6th grade, respectively.

To summarize, children require executive working-memory resources to solve simple addition problems. Even the simple task of saying an answer displayed on the screen (“naming”) relies on executive resources. Retrieving an answer from long-term memory, however, does need even more executive resources. As children grow older, they become more efficient (faster) in the execution of retrieval and counting strategies but not in the execution of the transformation strategy. Increases in strategy efficiency are accompanied with decreases in working-memory involvement. More specifically, higher retrieval and counting efficiencies reduced the requirements of executive resources, so that the negative impact of an executive load deceased with age. The executive resources needed in the naming task, however, stayed equal across grades. The role of working memory in the transformation strategy (which relied most heavily on executive resources) did not change across grades either: all children relied equally heavily on their working memory to use this strategy.

Strategy selection

In order to investigate effects on strategy selection, a 3 x 2 x 3 ANOVA was conducted on percentages strategy use (in the choice condition), with Grade (4th, 5th, 6th) as between-subjects factor and Load (no load vs. load) and Strategy (retrieval, counting, and transformation) as within-subjects factors (see Table 3).

The main effect of Strategy was significant, $F(2,57) = 31.91$, $MS_e = 2059$. Retrieval was used more frequently than transformation, $F(1,58) = 25.28$, which was in its turn used more frequently than counting, $F(1,58) = 3.70$. Strategy further interacted with Grade, $F(4,116) = 2.64$. Retrieval use increased between 4th and 5th grade, $F(1,58) = 6.85$ but did not change between 5th and 6th grade, $F(1,58) = 1.63$. Transformation use decreased between 4th and 5th grade, $F(1,58) = 10.79$ but did not change between 5th and 6th grade, $F(1,58) = 1.31$. Counting, finally, was equally frequently used between 4th and 5th grade and between 5th and 6th grade, both $F(1,58) < 1$. The Load x Strategy and Load x Strategy x Grade interactions did not reach significance.

To summarize, all strategies were used by the children, although retrieval was used more frequently than transformation and counting. Retrieval use also increased as children grew older. No effects of load on strategy selection were observed.

Individual differences

Table 4 displays means of each individual-difference variable for each grade. The results of a one-way ANOVA with Grade as between-subjects variable are displayed in this table as well. The main effect of Grade was significant for arithmetic skill and processing speed, but not for digit span or math anxiety. Planned comparisons showed that the progress in arithmetic skill and processing speed was significant between 4th and 5th grade but not between 5th and 6th grade.

In order to test the influence of individual differences on children’s arithmetic strategy use, correlations between strategy efficiencies, strategy selection and the individual differences were calculated (see Table 5). To consolidate the results presented in the previous sections, working-memory load was also included in these correlational analyses. Gender was coded as a dummy variable: girls were coded as -1 and boys were coded as 1. Grade was coded as two dummy variables. For the first one (4^{th} vs. 5^{th} grade), 4^{th} graders were coded as -1, 5^{th} graders were coded as 1, and 6^{th} graders were coded as 0. For the second one (5^{th} vs. 6^{th} grade), 4^{th} graders were coded as 0, 5^{th} graders were coded as -1, and 6^{th} graders were coded as 1. Working-memory load was coded as a dummy variable as well: no-load was coded as -1 and load was coded as 1.

The highest correlations appeared between the different types of strategy efficiency on the simple-arithmetic task (range .61 - .62). Children who efficiently retrieved simple-arithmetic facts from memory were also more efficient in efficiently employing non-retrieval strategies (counting and transformation).

Retrieval, transformation, and counting *efficiencies* further correlated with processing speed and arithmetic skill. Gender correlated with transformation efficiency only: transformation RTs were higher for boys than for girls. Fourth-grade children were slower than 5^{th} grade children on naming, retrieval, and counting, but not on transformation. Fifth-grade children were slower than 6^{th} grade children on the retrieval strategy only. Working-memory load correlated with naming RTs, retrieval RTs, and transformation RTs.

Strategy *selection* was also influenced by individual-difference variables. The retrieval strategy was more frequently used by children with higher processing speeds and higher arithmetic skills. Direct fact retrieval was further used more frequently by 5^{th} grade children than by 4^{th} grade children, but it did not correlate with the contrast 5^{th} vs. 6^{th} grade. Finally, retrieval use was higher in low-anxious children than in high-anxious children and higher in boys than in girls.

The relations between strategy efficiency and strategy selection on the one hand and grade and working-memory load on the other hand are thus in agreement with the results previously reported. Children become more efficient in the execution of naming, retrieval, and counting strategies, whereas the efficiency of the transformation strategy does not increase across grades. The frequency of retrieval use also gets higher as children grow older. Working-memory load, finally, predicted all strategy efficiencies except counting, and did not predict strategy selection.

Table 5 revealed other noteworthy correlations as well. Math anxiety, for example, correlated with digit span and with arithmetic skill: high-anxious children reached lower digit spans and lower arithmetic skill scores. The correlation between math anxiety and digit span is in agreement with results obtained by Ashcraft and Kirk (2001), who observed that adults' working-memory span was negatively correlated with math anxiety. Although working memory cannot be equated with short-term memory (cf. supra), both results indicate that higher math anxiety scores go hand in hand with lower capacities for information storage and/or processing. Math-anxious participants are often occupied by worries and intrusive thoughts when performing arithmetic tasks (Ashcraft & Kirk, 2001; Faust et al., 1996). Because such intrusive thoughts load on storage and processing resources, high-anxious participants exhibit lower short-term-memory and working-memory capacities. The correlation between math anxiety and arithmetic skill corroborates the results obtained by Ashcraft (1995; Ashcraft & Faust, 1994; Ashcraft & Kirk, 2001; Faust et al., 1996), who observed that complex-arithmetic performance was worse in high-anxious adults than in low-anxious adults.

Gender correlated with processing speed and math anxiety. Girls scored higher on the math anxiety questionnaire than boys. Girls were also faster on the processing speed task than boys. The correlation between math anxiety and gender has been found previously: Ashcraft (1995) observed that highly anxious women (top quartile on anxiousness scale) scored almost one SD higher on a math-anxiety scale than highly anxious men. Based on questionnaire results, however, it is impossible to rule out the possibility that females are just more honest in reporting their feelings than males are. The fact that girls were better on the processing speed test is in agreement with previous findings showing an advantage of females over males in perceptual speed (e.g., Kimura, 1992).

Subsequent hierarchical regression analyses assessed which variables contributed unique variance to the dependent variables naming efficiency, retrieval efficiency, transformation efficiency, counting efficiency, and retrieval frequency (see Appendix 1). In the 1st Model, we investigated whether the relationship between the independent variables (arithmetic skill, working-memory load, processing speed, math anxiety, gender, and digit span) and the respective dependent variable was maintained when age-related changes were accounted for (df = 1,118). Age-related changes indeed explained a large part of the variance: *grade* accounted for 10% of the variance in naming efficiency, $F(2,119) = 6.40$; for 24% of the variance in retrieval efficiency, $F(2,119) = 18.10$; for 6% of the variance in transformation efficiency, $F(2,119) = 3.62$; for 22% of the variance in counting efficiency, $F(2,119) = 16.94$; and for 10% of the variance in retrieval frequency, $F(2,119) = 6.55$.

In Model 1, we see that unique variance was found for arithmetic skill in predicting all four measures of simple-arithmetic strategic performance. Therefore, we investigated in Model 2 which variables were significant predictors when grade and arithmetic skill were controlled for (df = 1,116). In the 3rd model (df = 1,115), working-memory load was added to Model 2, whereas in the 4th model (df = 1,115), processing speed was added to Model 2.

Model 4 revealed that *working-memory load* contributed unique variance to naming efficiency, retrieval efficiency, and transformation efficiency, even when grade, arithmetic skill, and processing speed were controlled for. However, working-memory load did not contribute unique variance to counting efficiency or retrieval frequency. *Processing speed* contributed unique variance to naming efficiency, transformation efficiency, and retrieval frequency when grade was controlled for (Model 1). However, when working-memory load was entered in the model as well, processing speed was significant for naming efficiency only (Model 3). *Math anxiety* predicted retrieval efficiency and retrieval frequency. This contribution was significant, even in Models 3 and 4. *Gender*, finally, contributed unique variance to transformation efficiency (with boys being less efficient than girls), but this effect disappeared when processing speed was controlled for (Model 4). However, gender did contribute unique variance to retrieval frequency in all four models.

Several results obtained in the hierarchical regression results attract attention. First, although *processing speed* correlated with all four measures of simple-arithmetic strategic performance, processing speed did not contribute unique variance to any of these variables once working-memory load was entered in the analysis. Processing speed was significant for naming efficiency only. Second, *arithmetic skill* still contributed unique variance to the four simple-arithmetic performance measures once grade-related differences were controlled for. However, arithmetic skill did not predict naming efficiency although both variables did correlate with each other. Third, partialing grade, arithmetic skill, and processing speed did not eliminate the significant role that *working memory* plays in predicting naming efficiency, retrieval efficiency, and transformation efficiency. Fourth, although *math anxiety* correlated with retrieval frequency only, regression analyses showed that it predicted both retrieval frequency and retrieval efficiency, even in models 3 and 4. When free to choose the strategy they want (i.e., in choice conditions), high-anxious children less often made use of the retrieval strategy than low-anxious children, but when high-anxious children were required to use retrieval (i.e., in no-choice/retrieval conditions) they sped up their retrieval use. Finally, the regression analyses uncovered a possible underlying cause of the correlation between *gender* and transformation efficiency. As girls had higher levels of processing speed than boys (cf. Table 5), the correlation between gender and transformation efficiency might be caused by gender differences in processing speed. Indeed, gender did not contribute unique variance to transformation efficiency when processing speed was entered in the analysis. However, gender contributed unique variance to retrieval frequency, even in models 3 and 4. Retrieval use was more frequent in boys than in girls and this effect persisted even when grade, arithmetic skill, processing speed, and working-memory load were controlled for.

General Discussion

The role of working memory in children's strategy efficiency and strategy selection

The present results show that school-aged children rely on working-memory resources to perform simple-arithmetic problems. Taxing children's executive working-memory resources resulted in poorer arithmetic performance: children of all ages executed strategies less efficiently. The impact of an executive working-memory load on children's *retrieval* efficiency is in agreement with comparable results obtained in adults (e.g., Anderson, Reder, & Lebiere, 1996; Imbo & Vandierendonck, unpublished results) and indicates that working-memory resources are needed to select information from long term memory (Barrouillet & Lépine, 2005; Barrouillet, Bernardin, & Camos, 2004; Cowan, 1995, 1999; Lovett, Reder, & Lebière, 1999). It is important to note that the impact of the executive working-memory load was larger when answers had to be retrieved from long-term memory than when answers were provided to the children (i.e., the 'naming' condition). Presumably, except for retrieval of the correct answer, the processes of digit encoding, pronouncing, et cetera, were equal in the naming condition and the retrieval condition.

This result shows that retrieval of the correct answer and inhibition of incorrect answers do rely on executive working-memory resources. Recently, the executive function of inhibitory control has been shown to contribute to emergent mathematic skills in preschool children (Espy et al., 2004).

The role of working memory was larger in *non-retrieval* strategies than in direct memory retrieval, a result obtained in adult studies as well (Imbo & Vandierendonck, unpublished results). Indeed, in addition to the fact that procedural strategies (transformation and counting) are composed of multiple retrievals from long-term memory, these strategies also contain several processes which might require *extra* executive resources, such as performing calculations, manipulating interim results, and monitoring counting processes.

The arithmetic performances of normally developing children under executive working-memory load can be compared with arithmetic performances of mathematically impaired children, who are slower in solving arithmetic problems (e.g., Geary, 1993; Hitch & McAuley, 1991; Passolunghi & Siegel, 2001; Siegel & Linder, 1984; Siegel & Ryan, 1989; Swanson, 1993). This impairment has often been attributed to limitations in working memory, and especially to limitations in the executive working-memory component (e.g., McLean & Hitch, 1999; Passolunghi & Siegel, 2004). That lower arithmetic performance can be caused by limitations in working memory was confirmed by the present results, in which executive working-memory resources (of normally developing children) were limited experimentally.

The development of the role of working memory

The main goal of the present study was to investigate age-related changes in the ratio of available working-memory resources against simple-arithmetic task demands. The main conclusion is that the negative impact of an executive working-memory load decreases as children grow older. This conclusion corroborates the assertion that more working-memory resources are needed during the initial phases of skill acquisition and that fewer working-memory resources are needed with learning, namely when procedural strategies are used less frequently and retrieval strategies more frequently (Ackerman, 1988; Ackerman & Cianciolo, 2000; Geary et al., 2004; Siegler, 1996). Based on the results obtained in the present study, we infer that the declining impact of working-memory load is caused by age-related changes in strategy efficiency and strategy selection, but not by age-related changes in overall processing costs. All effects are discussed below.

First, the frequency of retrieval use increased across grades: 5th and 6th grade children used retrieval more often than 4th grade children. As direct memory retrieval is less effortful and requires fewer working-memory resources than non-retrieval strategies such as counting and transformation (cf. no-choice data), more frequent retrieval use goes hand in hand with lower working-memory involvement. Otherwise stated, more frequent retrieval use leaves more working-memory capacity free for other usages. This spare capacity can then be applied in the executive secondary task.

Second, retrieval efficiency increased across grades: direct memory retrieval took longer in 4th grade than in 5th grade, in which it still took longer than in 6th grade. More efficient retrieval use results from stronger problem-answer associations for the correct answer, and weaker problem-answer associations for the neighboring incorrect answers. Stronger associations between the problem and its correct answer reduce the amount of executive working-memory resources needed to inhibit incorrect answers.

Third, counting efficiency increased across grades: counting was slower in 4th grade than in 5th and 6th grade. As counting gets more efficient, fewer working-memory resources are needed, which reduces the working-memory involvement across age. The increase in counting efficiency might be caused by increases in retrieval and procedural efficiency, increases in processing speed, and increases in speech rate. The faster children can count, the less information that has to be protected from decay. Importantly, transformation efficiency did not change across grades, and neither did the effect of working-memory load on transformation efficiency.

Finally, results showed that the age-related decline in the impact of working-memory load could not be due to developmental changes in overall processing costs. Although naming RTs were larger in 4th grade than in 5th and 6th grade, the effect of working-memory load on naming did not decrease with age. To conclude, the changing ratio between working-memory involvement on the one hand and simple-arithmetic performance on the other hand was due to age-related changes in strategy selection and strategy efficiency (for retrieval end counting), but not to age-related changes in general processes such as encoding and pronunciation.

Importantly, our conclusions are in agreement with a recent fMRI study in which 8- to 19-year old subjects' arithmetic performance was tested (Rivera, Reiss, Eckert, & Menon, 2005). Rivera and colleagues (2005) observed that the activation in the prefrontal cortex decreased with age, suggesting that younger subjects need more working-memory and attentional resources to achieve similar levels of mental arithmetic performance. The activation of the hippocampus, the dorsal basal ganglia, and the parietal cortex decrease with age as well, suggesting greater demands on declarative, procedural, and visual memory systems in younger than in older children (Qin et al., 2004; Rivera et al., 2005).

Future research may use the method adopted here (i.e., a combination of the dual-task method and the choice/no-choice method) to investigate *which* executive resources come into play in children's arithmetic strategy performance. Previous (correlational) research suggests that both inhibition and memory updating play a role in children's arithmetic problem solving (e.g., Passolunghi et al., 1999; Passolunghi & Pazzaglia, 2005).

The influence of individual differences on children's strategy use

Digit span. Digit span did not correlate with strategy efficiency or strategy selection measures. This is at variance with previous studies in which a relation between short-term memory and arithmetic ability was observed (e.g., Hecht et al., 2001; Geary et al., 1991, 2000a; Hitch & McAuley, 1991; Passolunghi & Siegel, 2001; Siegel & Ryan, 1989; Swanson & Sachse-Lee, 2001). It should be noted though, that a number of these studies included mathematically disabled children without taking reading ability or general intelligence into account. In as many other studies, no relation between short-term memory and mathematical ability was observed (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Bull & Johnston, 1997; Geary et al., 2000a; Passolunghi et al., 1999; Passolunghi & Siegel, 2004; Swanson, 2006, Temple & Sherwood, 2002), which is in agreement with the present results. It seems that individual differences in short-term memory do not play an important role in children's simple-arithmetic performance. Individual differences in working memory, on the other hand, do play a role in children's simple-arithmetic strategy use. Indeed, correlations between working-memory measures and mathematics ability have been found consistently (e.g., Bull et al., 1999; Bull & Scerif, 2001; Geary et al., 1999; McLean & Hitch, 1999; Noël et al., 2004; Passolungi et al., 1999; Passolunghi & Siegel, 2004; Swanson, 2004, 2006; Swanson & Beebe-Frankenberger, 2004; Swanson & Sachse-Lee, 2001, van der Sluis et al., 2004).

In our study with normally developing children, working-memory (as loaded by the CRT-R task) but not short-term memory (as tested with the digit span) was related to arithmetic performance. We thus agree with Steel and Funnell (2001) in asserting that the number of items that can be stored in memory is less important than the ability to control attention and maintain information in an active, quickly retrievable state (see also Engle, 2002). The present results are also in agreement with most of the recent studies on mathematically disabled children. Children with mathematics learning difficulties might suffer from a working-memory deficit (Geary, 2004) rather than a short-term memory deficit.

Processing speed. We observed that retrieval efficiency, transformation efficiency, counting efficiency, and retrieval frequency were lower in children with a low processing speed than in children with a high processing speed. Correlations between processing speed and arithmetic ability have been observed previously (e.g., Bull & Johnston, 1997; Durand, Hulme, Larkin, & Snowling, 2005; Kail & Hall, 1999). Kail and Hall (1999) hypothesized that faster processing is associated with faster retrieval of problem solving heuristics. The present research is consistent with their hypothesis in that we observed that fast-processing children were more likely than slow-processing children to select fast retrieval strategies. It should be noted, though, that the present results are in disagreement with Noël et al.'s (2004) results, who observed that slow-processing children used retrieval more frequently than fast-processing children. Our results, however, are consistent with the expectation that fast-processing children develop stronger problem-answer associations in long-term memory, resulting in more frequent retrieval use.

According to Bull and Johnston (1997), slow processing children may experience several difficulties. They may be slower in general information processing; however, they may also simply lack the automaticity to perform basic arithmetic operations. Based on the results obtained in the hierarchical regression analyses, the first explanation seems more plausible. Indeed, once age and working memory were controlled for, processing speed did not contribute unique variance anymore to any of the four arithmetic performance measures. Hence, the relation between processing speed and arithmetic performance is rather due to an age-related retardation and to general working-memory deficits than to specific deficits in processing and automatizing numbers and number facts.

Arithmetic skill. High correlations between arithmetic skill on the one hand and strategy selection and strategy efficiency on the other hand were observed. Moreover, arithmetic skill contributed unique variance when age was partialed from the analyses. Obviously, children who frequently use direct memory retrieval, who can efficiently retrieve answers from long-term memory, and who can efficiently execute non-retrieval strategies are in a good position to acquire general computational skills, resulting in good performance on general math attainment tasks. This agrees well with Hecht et al.'s (2001) finding that, in elementary-school children, simple-arithmetic efficiency is a significant predictor of later variability in general computational skills, even when phonological skills are controlled for.

Math anxiety. Math anxiety did not correlate with efficiencies at different strategies. This is in agreement with the assertion that math anxiety only affects complex-arithmetic performance but not simple-arithmetic performance (Ashcraft, 1995; Faust et al., 1996). Math anxiety did indeed correlate with performance on the (more complex) arithmetic-skill test: high-anxious children solved fewer problems than low-anxious children, indicating more efficient complex problem solving in the latter than in the former.

Math anxiety further correlated with simple-arithmetic strategy selection: high-anxious children used retrieval less often than low-anxious children. This effect of math anxiety on strategy selection can easily be explained on the basis of the strategy choice model of Siegler and Shrager (1984). In their model, each participant has his or her own confidence criterion. When solving simple-arithmetic problems, the strength of the problem-answer association is compared with this subjective confidence criterion. If the problem-answer associative strength exceeds the confidence criterion, the answer is emitted. If the problem-answer associative strength does not exceed the confidence criterion, then the child may continue to search memory for other candidate answers or may resort to a procedural strategy to compute the answer. If we suppose that anxious children set very high confidence criteria in order not to produce any incorrect answers, problem-answer associations will only infrequently cross those criteria, resulting in less frequent retrieval use and more frequent procedural use.

Gender. Girls were more efficient in transformation use whereas the retrieval strategy was used more frequently by boys. More frequent retrieval use in boys has been observed in previous studies (Carr, 1996; Carr & Jessup, 1997; Davis & Carr, 2002), and has been attributed to the effect of temperament (Davis & Carr, 2002). More efficient transformation use in girls than in boys has not been reported yet, but the present study showed that this observation might be related to by gender differences in processing speed (cf. the hierarchical regression analyses). The more efficient transformation use in girls than in boys might also help to explain the gender difference in strategy selection: as girls are reasonably fast in applying the transformation strategy, they might opt not to switch to the retrieval strategy, which is for them only slightly faster. In boys, on the other hand, the retrieval strategy is considerably faster than the transformation strategy, leading them to choose the fastest strategy (retrieval) more often. It is noteworthy that no gender differences were observed in retrieval efficiency. In previous studies, males were observed to be faster retrievers than females, both in children (Royer et al., 1999) and adolescents (Imbo et al., in press). More efficient retrieval use in boys than in girls is thus not consistently found across studies.

What causes such gender differences in arithmetic performance? According to Geary (1999) and Royer et al. (1999), gender differences in arithmetic performance are not likely to be biologically based. Social and occupational interests, on the contrary, seem to be a more reasonable cause. Royer et al. (1999) suppose that boys engage in out-of-school activities that provide them with additional practice on the manipulation of mathematical information. Geary, Saults, Liu, & Hoard (2000) believe that the male advantage in mathematical problem solving is due to a male advantage in spatial cognition. In sum, it is clear gender differences in arithmetic performance and their sources are not known sufficiently and should be investigated further.

Summary

In the present study, two approved methods were combined in order to investigate the development of working-memory involvement in children's arithmetic strategy use. The dual-task method permitted an on-line investigation of working-memory involvement in arithmetic performance, and the choice/no-choice method permitted achieving reliable strategy selection and strategy efficiency data. As far as we know, the combination of both methods has not yet been used in child studies. The results showed that, across development, the effect of an executive working-memory load decreased when retrieval was used more frequently and when strategies were executed more efficiently. However, the age-related decline in working-memory use was not due to developmental changes in other, more general processes, which required working-memory resources across all ages. Individual-difference variables (gender, math anxiety, arithmetic skill, and processing speed) accounted for differences in strategy selection and strategy efficiency as well. Arithmetic skill and working memory contributed more unique variance to arithmetic performance than processing speed and short-term memory did. Math anxiety and gender predicted some but not all of the arithmetic performance measures. Future research on working memory, strategy use, and mental arithmetic may investigate other arithmetic operations (subtraction, multiplication, division), other working-memory resources (phonological loop and visuo-spatial sketchpad), and other individual differences (e.g., motivation, intelligence, etc.)

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Foot notes

1. We are grateful to these authors for providing us the stimuli used in their visual number matching task.
2. To test whether RTs did change linearly across grades, contrast values were -1 for 4th grade, 0 for 5th grade, and 1 for 6th grade.

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Table 1

Mean accuracies (%) and mean correct RTs (milliseconds) on the CRT-R task as a function of Grade and Primary task. Standard errors between brackets.

Accuracies	4th grade	5th grade	6th grade
No primary task	46 (9)	76 (8)	77 (9)
Naming	42 (7)	66 (7)	70 (7)
No-choice/retrieval	26 (6)	43 (6)	46 (6)
No-choice/transform	29 (6)	48 (6)	45 (6)
No-choice/count	26 (4)	59 (6)	50 (6)
Choice	25 (6)	44 (5)	44 (6)
RTs	**4th grade**	**5th grade**	**6th grade**
No primary task	772 (49)	739 (48)	743 (49)
Naming	944 (54)	786 (52)	790 (54)
No-choice/retrieval	1052 (50)	1028 (48)	1066 (50)
No-choice/transform	1026 (47)	1024 (46)	1010 (47)
No-choice/count	980 (40)	975 (39)	1001 (40)
Choice	1034 (36)	1054 (35)	964 (36)

Table 2

Mean corrects RTs (in milliseconds) on the simple-arithmetic task (in no-choice conditions) as a function of Grade, Load, and Task. Standard errors between brackets.

		4th grade	5th grade	6th grade
Naming	No load	641 (22)	525 (22)	511 (22)
	Load	989 (52)	794 (50)	790 (52)
Retrieval	No load	1650 (88)	1382 (86)	1115 (88)
	Load	2122 (106)	1763 (103)	1387 (106)
Transformation	No load	2550 (241)	2006 (235)	1816 (241)
	Load	3177 (325)	2610 (317)	2404 (325)
Counting	No load	4299 (360)	2684 (351)	2561 (360)
	Load	4778 (376)	2955 (367)	2644 (376)

Table 3

Mean percentages strategy use (in the choice condition) as a function of Grade and Load. Standard errors between brackets.

		4^{th} grade	5^{th} grade	6^{th} grade
Retrieval	No load	46 (7)	67 (7)	60 (7)
	Load	48 (7)	76 (7)	60 (7)
Transformation	No load	41 (6)	15 (6)	22 (6)
	Load	40 (6)	6 (6)	22 (6)
Counting	No load	12 (5)	18 (5)	18 (5)
	Load	12 (5)	15 (4)	18 (5)

Table 4

Means and standard deviations of the individual-difference variables across grades. Results of the ANOVAs with Grade as between-subjects factor are displayed in the three rightmost columns.

	4^{th} grade mean (SD)	5^{th} grade mean (SD)	6^{th} grade mean (SD)	$F(2,58)$ main effect	$F(1,58)$ 4^{th} vs. 5^{th}	$F(1,58)$ 5^{th} vs. 6^{th}
Digit span	5.5 (1)	5.8 (1)	5.7 (1)	0.66	1.28	0.04
Processing speed	96 (14)	79 (15)	72 (10)	16.80**	15.73**	3.08°
Arithmetic skill	46 (5)	53 (7)	57 (6)	19.76**	15.99**	2.84°
Math anxiety	2.3 (1)	2.4 (1)	2.1 (1)	0.42	0.15	0.85

° $p < .10$ * $p < .05$ ** $p < .01$

Table 5 (next page)

Correlations between naming RTs, retrieval RTs, transformation RTs, counting RTs, percentages retrieval use, working-memory load, and the individual-difference variables. Note that efficiency and speed measures are expressed in RTs, so *higher* RTs indicate *lower* efficiencies.

	Retrieval Eff.	Transf. Eff.	Count Eff.	Retrieval %	Digit Span	Proces. Speed	Arithm. Skill	Math Anxiety	Gender	4th vs. 5th Grade	5th vs. 6th Grade	WM Load
Naming Eff.	.52**	.42**	.37**	-.08	.00	.34**	-.30**	-.12	.12	-.26**	-.01	.62**
Retrieval Eff.		.62**	.61**	.00	-.01	.39**	-.59**	-.05	.11	-.24**	-.24**	.35**
Transf. Eff.			.61**	-.11	.01	.35**	-.56**	.02	.20*	-.17	-.06	.23*
Count Eff.				-.07	-.02	.39**	-.49**	.03	.02	-.38**	-.04	.08
Retrieval %					-.02	-.27**	.32**	-.28**	.18*	.32**	-.16	.05
Digit Span						-.23*	.14	-.20*	-.11	.15	-.05	---
Proces. Speed							-.58**	-.07	.30**	.42**	.18*	---
Arithm. Skill								-.19*	-.03	.05	-.12	---
Math Anxiety									-.25**	-.28*	.05	---
Gender										---	---	---
4th vs. 5th Grade											---	---
5th vs. 6th Grade												---

* $p < .05$ ** $p < .01$

Appendix 1

Hierarchical regression analyses for naming efficiency, retrieval efficiency, transformation efficiency, counting efficiency, and retrieval frequency.

	Model1			Model 2			Model 3			Model 4		
Naming efficiency	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*
Arithm. skill	.020	2.68	-.181									
WM load	.382	86.63**	.618	.386	90.32**	.622				.385	94.41**	.621
Proces. speed	.041	5.66*	.256	.027	3.69	.219	.026	6.47*	.217			
Math anxiety	.017	2.22	-.130	.027	3.65	-.169	.026	6.34*	-.166	.018	2.44	-.140
Gender	.006	0.81	.081	.009	1.14	.096	.010	2.45	.105	.002	0.28	.049
Digit span	.002	0.20	.040	.003	0.35	.052	.003	0.68	.055	.007	0.92	.085
Retrieval efficiency	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*
Arithm. skill	.138	26.26**	-.474									
WM load	.124	22.85**	.353	.122	28.87**	.350				.122	28.62**	.350
Proces. speed	.016	2.58	.161	.000	0.00	.001	.000	0.00	.000			
Math anxiety	.007	1.03	-.082	.030	6.03	-.179	.030	7.41**	-.178	.032	6.24*	-.187
Gender	.000	0.01	.007	.001	0.17	.031	.001	0.30	.037	.001	0.19	0.34
Digit span	.001	0.15	.032	.004	0.68	.061	.004	0.89	.063	.004	0.70	0.63

* $p < .05$ ** $p < .01$. Model 1 = age controlled (*df* per test= 1,118). Model 2 = age + arithmetic skill controlled (*df* per test= 1,116). Model 3 = age + arithmetic skill + working-memory load controlled (*df* per test= 1,115). Model 4 = age + arithmetic skill + processing speed controlled (*df* per test= 1,115).

Appendix 1 (continued)

Transformation efficiency	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*
Arithm. skill	.208	35.24**	-.582									
WM load	.053	6.97**	.229	.048	8.58**	.218				.047	8.66**	.218
Proces. speed	.063	8.47**	.316	.014	2.42	.158	.014	2.55	.157			
Math anxiety	.000	0.01	.009	.018	3.15	-.139	.018	3.30	-.138	.013	2.22	-.119
Gender	.028	3.58	.171	.029	5.11	.177	.030	5.67*	.180	.020	3.52	.154
Digit span	.002	0.20	.040	.005	0.78	.069	.005	0.86	.070	.008	1.43	.094
Counting efficiency	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*
Arithm. skill	.069	11.38**	-.335									
WM load	.006	0.88	.076	.006	1.01	.078				.006	1.00	.078
Proces. speed	.019	2.93	.173	.003	0.45	.070	.003	0.45	.069			
Math anxiety	.000	0.04	.016	.002	0.28	-.042	.002	0.27	-.042	.001	0.16	-.033
Gender	.003	0.45	-.056	.001	0.14	-.031	.001	0.13	-.030	.002	0.37	-.052
Digit span	.002	0.27	.043	.004	0.69	.065	.004	0.69	.066	.006	0.93	.078

* $p < .05$ ** $p < .01$. Model 1 = age controlled (*df* per test= 1,118). Model 2 = age + arithmetic skill controlled (*df* per test= 1,116). Model 3 = age + arithmetic skill + working-memory load controlled (*df* per test= 1,115). Model 4 = age + arithmetic skill + processing speed controlled (*df* per test= 1,115).

Appendix 1 (continued)

Retrieval frequency	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*	*R*Δ	*F*	*Beta*
Arithm. skill	.053	7.30**	.293									
WM load	.003	0.38	.054	.004	0.49	.060				.004	0.50	.060
Proces. speed	.030	4.13*	-.219	.010	1.43	-.135	.010	1.43	-.136			
Math anxiety	.091	13.31**	-.304	.065	9.58**	-.262	.064	9.51**	-.261	.079	11.96**	-.295
Gender	.038	5.15*	.199	.035	4.94*	.193	.035	4.97*	.194	.051	7.52**	.246
Digit span	.004	0.52	-.063	.006	0.89	-.082	.006	0.88	-.081	.010	1.41	-.104

* $p < .05$ ** $p < .01$. Model 1 = age controlled (*df* per test= 1,118). Model 2 = age + arithmetic skill controlled (*df* per test= 1,116). Model 3 = age + arithmetic skill + working-memory load controlled (*df* per test= 1,115). Model 4 = age + arithmetic skill + processing speed controlled (*df* per test= 1,115).