



HAL
open science

Executive Functions and Strategic Aspects of Arithmetic Performance: The Case of Adults' and Children's Arithmetic

Patrick Lemaire

► **To cite this version:**

Patrick Lemaire. Executive Functions and Strategic Aspects of Arithmetic Performance: The Case of Adults' and Children's Arithmetic. *Psychologica Belgica*, 2010, 50 (3-4), pp.335-352. 10.5334/pb-50-3-4-335 . hal-04503222

HAL Id: hal-04503222

<https://hal.science/hal-04503222>

Submitted on 13 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

EXECUTIVE FUNCTIONS AND STRATEGIC ASPECTS OF ARITHMETIC PERFORMANCE: THE CASE OF ADULTS' AND CHILDREN'S ARITHMETIC

Patrick LEMAIRE
Université de Provence & CNRS

In this paper, we provide an overview of three important issues regarding working-memory/executive functions (WM/EF), strategies, and cognitive development in the domain of arithmetic. One goal of this overview is to bring some lights on the depth and breadth of the most valuable contributions that André Vandierendonck and his collaborators made on these issues. First, we consider strategic aspects of arithmetic performance and strategic development in arithmetic. Second, the role of WM/EF on arithmetic performance and arithmetic strategies is discussed. Finally, some data are reported on how age-related changes in WM/EF affect strategic development in arithmetic. For each of these issues, we highlight how the works carried out by André Vandierendonck and his colleagues, when integrated in the broader context of research on cognitive arithmetic, contributed to our further understanding of participants' performance and age-related changes in this performance.

The main goal of research in arithmetic is to understand processes and mental representations used by people to solve arithmetic problems such as 8×4 , $23 + 76$, or 34×89 . Arithmetic has been a very important domain to investigate for André Vandierendonck. His research in this domain has made numerous important contributions. In fact, he authored or co-authored over 20 papers in peer-reviewed journals on arithmetic in the past decade. His research interests concerned both specificities of this domain and how general cognitive constraints affect participants' arithmetic performance and changes in this performance with age. His research has made important contributions to issues as varied as how participants' performance in arithmetic is influenced by problem features (e.g., odd/even status of numbers, size of problems, type of arithmetic operations, carry/borrow processing), individual differences (e.g., role of gender, skills, working-memory span), and by the type of processes (e.g., role of executive processes, strategies) used to solve arithmetic problems. I share most of André's interests and views in my own research. In fact, many of his findings and views have influenced my own

Patrick LEMAIRE, Université de Provence, Case D, 3 Place Victor Hugo, 13331 Marseille, France, tel. +33.4.88.57.69.01, E-mail: Patrick.Lemaire@univ-provence.fr

Key words: Working Memory, executive Functions, Strategies, Arithmetic, Cognitive Development.

research agenda and how I conducted research in arithmetic. To illustrate this, I shall review here findings of both André's and my research on three specific issues. First, I shall discuss some data on the role of strategies and strategic development in arithmetic. Second, I shall consider recent findings on the role of working-memory/executive functions (WM/EFs) in arithmetic and strategic aspects of arithmetic performance. Finally, how age-related changes in WM/EFs influence strategic development in arithmetic is a most recent issue that has started to be scrutinized, as we shall see. The first two issues have been greatly investigated by André and his collaborators. They have carried out much less research on the last issue, but I shall illustrate how their research has a number of implications on it and open up for new research strategy that, in the future, may prove extremely useful to further our understanding of arithmetic development.

Strategies in Arithmetic

Both André's and my work have tried to understand the determinants of arithmetic problem solving performance. Previous research has shown that participants' performance is influenced by, among others, the type of strategies that participants use. Here, we present some findings regarding strategic variations in performance and strategic development in arithmetic, two topics in which André and his collaborators made invaluable contributions.

Strategic variations in arithmetic. Ever since the early days of Cognitive Psychology, researchers have found that participants accomplish cognitive tasks with a variety of strategies. A strategy is usually defined as "a procedure or a set of procedures to accomplish a high-level goal" (Lemaire & Reder, 1999, p. 365) or "a set of methods to accomplish a cognitive task » (Newell & Simon, 1972, p. 127). Investigating the strategies that people use to accomplish a task, how often they use each available strategy, and how they execute and select strategies on each problem has enabled cognitive psychologists important advances to understand participants' performance and experimental effects as varied as item, individual, and situational characteristics. This has also been the case in the specific domain of arithmetic problem solving.

The goal of research in arithmetic is to find out how participants solve simple (e.g., 8×4) or complex (e.g., 34×57) arithmetic problems and mental representations underlying participants' performance. Usually, participants are asked to accomplish two kinds of tasks, production or verification tasks. In production tasks, participants are given arithmetic problems (e.g., 3×5 , 14×67 ; $345 + 786$) and are asked to find a solution. In verification tasks, participants are presented arithmetic equations (e.g., $4 \times 8 = 31$; $35 + 67 < 100$) and have to say "true" or "false". In both kinds of tasks, participants use several

strategies, and strategies vary in relative efficacy.

Strategies in arithmetic problem verification tasks are determined with indirect approaches. In these approaches, the use of multiple strategies is inferred from the patterns of speed and accuracy that arise as a function of the factors that define the stimulus set. Both André and I used indirect approaches to investigate strategic aspects of verification task performance (e.g., Lemaire & Fayol, 1995; Lemaire & Reder, 1999; Vandorpe, De Rammelaere, & Vandierendonck, 2004). For example, Lynne Reder and I asked participants to verify two types of arithmetic problems, parity-match problems (e.g., $4 \times 38 = 154$) and parity-mismatch problems (e.g., $4 \times 38 = 153$). The parity of the proposed answer matches the parity of the correct answer in parity-match problems and mismatches the parity of the correct answer in the parity-mismatch problems. As can be seen in Figure 1, participants are faster in verifying arithmetic problems when the parity of the false proposed answer mismatches the parity of the correct answer (e.g., $4 \times 38 = 153$) than when both parities match (e.g., $4 \times 38 = 154$), especially in the high-mismatch condition (i.e., 80% of problems were mismatch problems). This parity effect has been interpreted as resulting from participants using two different strategies, one for each problem type. When they verify parity-match problems,

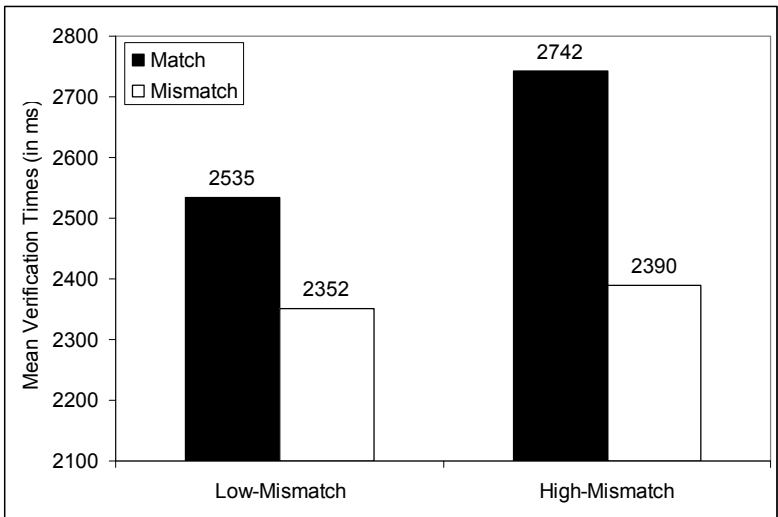


Figure 1

Data showing that participants are faster in verifying arithmetic problems when the parity of the false proposed answer mismatches the parity of the correct answer (e.g., $4 \times 38 = 153$) than when parity matches ($4 \times 38 = 154$), especially in the high-mismatch condition (i.e., 80% of problems were mismatch problems).

Data from Lemaire & Reder, 1999

they use the exhaustive verification strategy including encoding, calculating the correct answer, comparing the proposed and correct answers, making a “true/false” decision, and responding. When they verify parity-mismatch problems, they use a short-cut, parity checking strategy whereby they realize that the parity of the unit digit of proposed and correct answers are different and make a quick false decision. This quick parity checking strategy is used more quickly and more often when the proportion of parity-mismatch problems is large. André and his colleagues, following others, have found this parity effects while participants were verifying simpler, one-digit multiplication problems (e.g., $4 \times 7 = 29$ vs. $4 \times 7 = 26$; Vandorpe et al., 2004).

In production tasks, strategies used to solve arithmetic problems are investigated with direct approaches. In direct approaches, we collect as much external behavioral evidence (verbal protocols, video-recordings, direct observations) of strategies as possible. This can be illustrated in complex arithmetic problem solving task. Participants are often asked to find the solution of problems like 28×73 , $56 - 27$, or $37 + 58$ (e.g., Duverne & Lemaire, 2005, for a review). When participants use counting, they either count on their fingers (i.e., taking 4 fingers out of 7 fingers raised to find the correct result of $7 - 4$) or count mentally. When they retrieve directly the solution from their long-term memory (LTM), they are very fast and show no behavioral external evidence of counting. Usually strategies vary in efficacy, such that counting for example takes much longer than retrieving the solution directly from LTM. Some strategies are more efficient for some problems and other strategies are more efficient for other problems.

Strategic development in arithmetic. Adopting a strategy perspective enables a better understanding of the role of different factors and experimental conditions (like when participants have better performance while solving easy vs. hard problems or when asked to solve problems under some speed vs. accuracy pressure conditions). It also enables to understand individual differences, such as skills, cognitive status, or age. Like André and his colleagues, we conducted a number of studies investigating age-related changes in strategic variations. Our works have been conducted in both children and older adults. In all our works, we investigated four dimensions of strategic variations: strategy repertoire (i.e., which strategies are used in a given task?), strategy distribution (i.e., how often each strategy is used?), strategy execution (i.e., how fast is each available strategy executed?), and strategy selection (i.e., how do people choose among strategies?). Age-related changes during both cognitive development and cognitive aging involve changes in each of these strategic dimensions.

For example, when Siegler and I (Lemaire & Siegler, 1995) investigated the development of multiplication problem solving skills, we tested French second graders three times during the same school year (January, April, and

June) while they were learning basic multiplication facts. We found that during this school year, children (a) became much faster and more accurate at each testing session (they took 9.9 s, 5.5 s, and 3.3 sec in each of the first, second, and third testing sessions, respectively). However, magnitude of changes varied with the strategies that children used. When children used the retrieval strategy (i.e., retrieving the answer directly from LTM), they took 3.9 s on the first testing session and 2.9 s on the last testing session. When they used repeated addition (e.g., doing $4+4+4$ to calculate 3×4), they took 18.8 s and 11.8 s during the first and third testing sessions, respectively. Moreover, children moved from using available strategies equally often to using retrieval most often. More precisely, during the first session, children used retrieval on 38% of problems, repeated addition on 30% of problems and replied "I don't know" on 32% of problems. During the last session, they used retrieval on 92% of problems, repeated addition on 6% of problems, and replied "I don't know" on 2% of problems. In other words, this study showed that 7 year-old children improved at solving single-digit multiplication problems via selecting the fastest strategy more often and executing available strategies more quickly and accurately.

Such age-related changes in strategic aspects of arithmetic performance has since then been documented for other arithmetic operations, showing that it is not a specificity of one-digit multiplication problems. For example, Imbo and Vandierendonck (2007) asked fourth, fifth, and sixth graders to solve one-digit addition problems with the choice/no-choice method (Siegler & Lemaire, 1997). Three main strategies were tested: retrieval (i.e., directly retrieving the correct sum from LTM), changing (i.e., changing the problem by making an intermediate step to 10, like doing $9+1=10+5$ to solve $9+6$), and counting (i.e., counting subvocally by one until correct sum is reached, like doing $9+1+1+1+1$ to solve $9+4$). In the choice condition, participants were free to choose among the three strategies whichever strategy they want on each problem. Then, participants had to solve all problems with the retrieval strategy in the no-choice/retrieval condition, with the transforming strategy in the no-choice/transforming strategy condition, and with the counting strategy in the no-choice/counting strategy condition. Data in the no-choice conditions showed age-related differences in strategy execution. As can be seen from Figure 2, increase in speed with age varied with strategies used by children, such that largest increase was observed when participants executed the counting strategy and smallest increase was found for the retrieval strategy (with transforming in-between). Moreover, data on strategy use (see Figure 3) showed different strategy distributions in each age group. The oldest two groups of children used retrieval most frequently and the other two strategies on less than 25% of problems. Fourth graders used retrieval and transforming equally often and counting much less frequently.

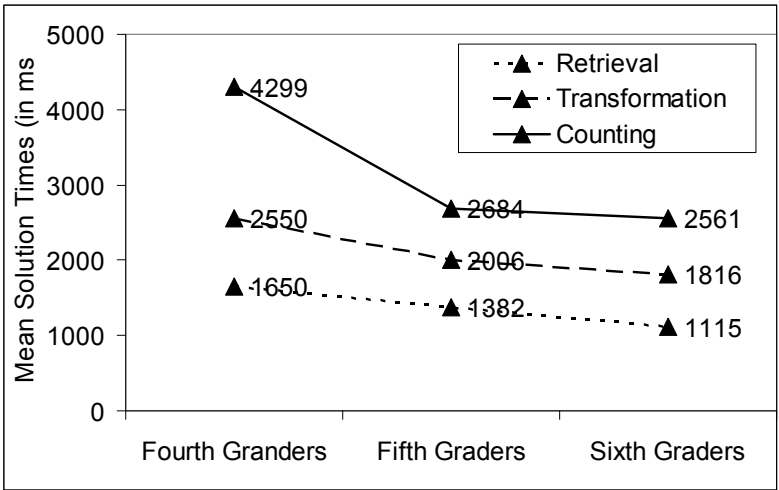


Figure 2

Data showing that age-related increase in speed is different for each strategy used by children to solve one-digit addition problems (data from Imbo & Vandierendonck, 2007)

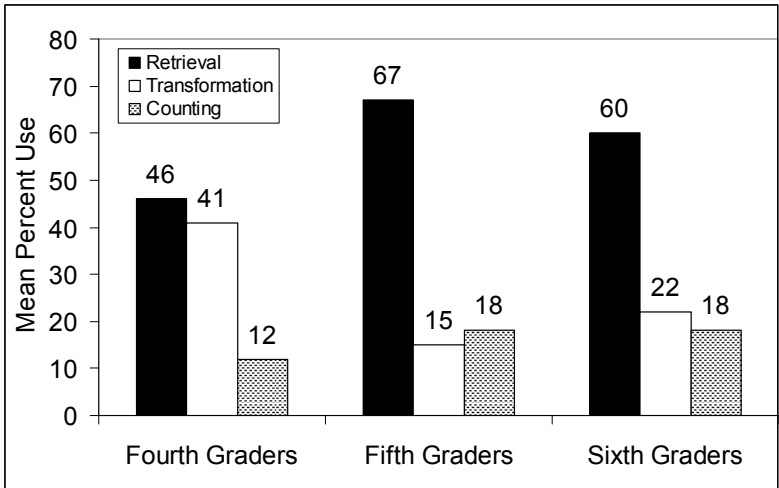


Figure 3

Data showing age-related changes in strategy distributions, with retrieval being used on most problems in fifth and sixth graders and being used equally often than transformation in fourth graders (data from Imbo & Vandierendonck, 2007)

Strategic development has also been investigated in complex arithmetic problem solving. For example, Lemaire and Calliès (2009) showed that age-related changes in effects of problem features depend on the type of strategies that children use. Lemaire and Calliès asked adults, fifth graders, and seventh graders to solve two-digit addition problems. They asked children to solve all problems with the full-decomposition strategy (i.e., adding tens first, decades second, and both sums third, like doing $20+50=70$; $4+3=7$; $70+7=77$ to solve $24+53$) in one condition and with the partial-decomposition strategy (i.e., adding first tens of the second number to the first number, like doing $24+50=74$; $74+3=77$) in another condition. They compared participants' performance for carry (e.g., $28+37$) and no-carry problems (e.g., $54+32$). As can be seen from Figure 4, participants were faster on no-carry problems than on carry problems. This carry effect decreased with increasing age. Moreover, these age-related changes in carry effects were not the same for each strategy, as they were larger while participants used the partial decomposition strategy than while using the full-decomposition strategy.

In sum, a number of studies in arithmetic, including ours and André's, have shown that arithmetic performance is best accounted for with a strategy perspective, as participants' performance depends on the type of strategies

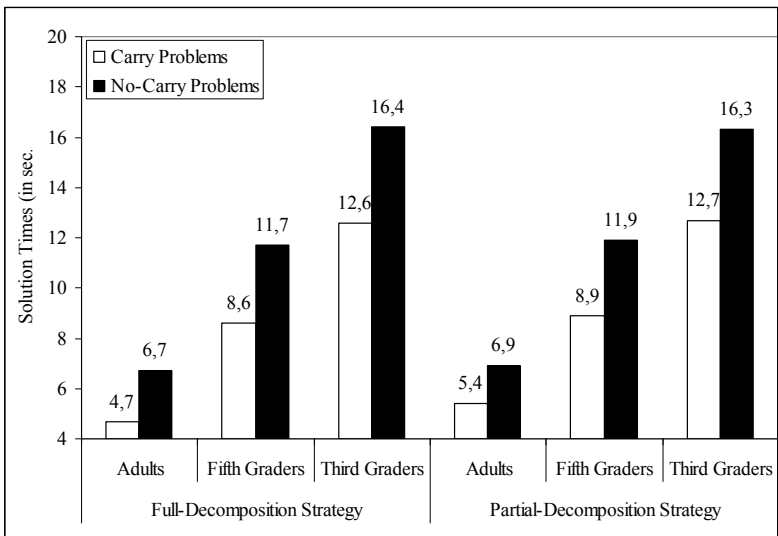


Figure 4

Data showing that children are faster when they solve no-carry, two-digit addition problems than carry problems, and that carry effects decreased with increasing age, and more so for the partial-decomposition strategy than for the full-decomposition strategy (data from Lemaire & Calliès, 2009)

they use. Moreover, age-related changes in arithmetic are best characterized by changes in strategic aspects of children's performance. These include changes in strategy repertoire, strategy distributions, strategy execution, and strategy selection. These strategic aspects can be investigated directly (like in studies videotaping children while they solve arithmetic problems, or in studies collecting verbal protocols on a problem-by-problem basis) or indirectly (like in studies investigating the performance on different types of problems, each of which being known to be solved with different strategies).

WM/EF and Arithmetic Problem Solving

The role of WM/EF in arithmetic performance. In a series of experiments, both André and I independently tried to determine whether working-memory resources influence arithmetic performance. We both used Alan Baddeley's theory of working-memory (Baddeley & Hitch, 1974) as a guide to address this issue. In a first series of experiments, my colleagues and I asked participants to verify simple multiplication problems (i.e., saying whether problems like $8 \times 4 = 32$ or 38 are true or false) under several working-memory load conditions (Lemaire, Abdi, & Fayol, 1996). For example, in one control condition, participants were asked to accomplish only the arithmetic problem verification task. In a second condition, so-called articulatory suppression (AS) condition, participants were asked to repeat "abcdef" (1 letter/1 sec.) while solving arithmetic problems. Following the dual-task logic, this latter condition tested the involvement of the phonological loop in arithmetic. We wanted to determine whether one of the most robust findings in the psychology of arithmetic would change as a function of WM load. This effect is the problem-size effect (PSE). It consists in better performance with small problems like 3×4 than with large problems like 7×8 . This effect indexes how fast people are to retrieve small and large products in LTM. It also indexes the use of backup, counting strategies, as people tend to use repeated addition more often on large problems than on small problems (e.g., Campbell & Xue, 2001; LeFevre et al., 1996a, b). Small problems have a better memory representation than large problems and are thus more easily activated and/or more often solved via retrieval. Larger PSE under the AS condition (compared to the control condition) was expected if retrieving basic arithmetic facts (and large problems in particular) requires working-memory resources in the phonological system and/or if depletion of WM resources lead participants to use backup strategies more often. As can be seen in Figure 5, although there was a trend toward increased PSE in AS, the PSE \times WM load interaction was actually not significant. This result was confirmed by a subsequent study ran by André Vandierendonck and his collaborators. They used almost exactly

the same design with two exceptions. First, they tested addition problems, and second they asked participants to constantly repeat “the” (at a rate of two or three times/sec) while verifying simple addition problems. Like we did for multiplication problems, they found no interaction between PSE and WM load condition. In fact, such finding is very important for the psychology of arithmetic as, to use André’s words, it “is not in agreement with models that assume that basic arithmetic facts are stored in a language-dependent verbal form” (De Rammelaere et al., 2001, p. 271). In these series of experiments, both André and I had independently tested a central-executive condition. It did not change the magnitude of PSE either. These effects of WM/EF on arithmetic performance have been replicated by many others, and their conditions of occurrence are now well documented (see De Stefano et al., 2004; LeFevre et al., 2005, for reviews)

The role of WM/EF in arithmetic strategy use and strategy execution. To better understand the role of WM/EF on arithmetic performance, with one of André’s Ph.D. students (who was visiting us for six months as an ERASMUS student) and a Ph.D. student of mine, we ran a study in which we looked at

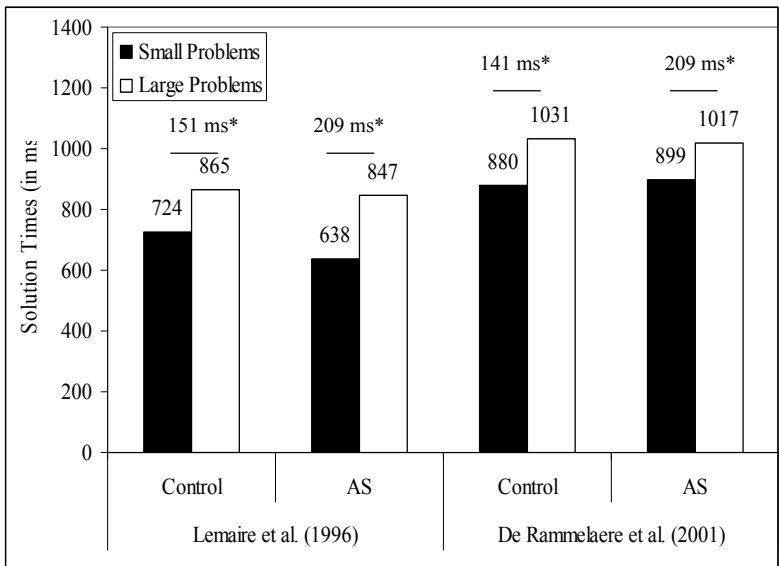


Figure 5

Data showing that articulatory suppression did not increase problem-size effect (i.e., difference in solution times between small and large arithmetic problems), suggesting that participants do not use working-memory resources to automatically retrieve solution to addition (Lemaire et al. 1996’s data) or multiplication (De Rammelaere et al. 2001’s data) problems from LTM

strategies (Imbo, Duverne, & Lemaire, 2007). In order to further understand the locus of WM/EF effects in arithmetic, we hypothesized that WM/EF would affect how participants select and execute arithmetic strategies. In this experiment, we asked participants to accomplish a computational estimation task. They were given two-digit multiplication problems and had to find approximate products. To do this, they could use two strategies, rounding-down (i.e., they rounded both operands down to the closest decades, like doing 40×50 to find an estimate for 43×58) or rounding-up (i.e., they rounded both operands up to the closest decades, like doing 50×60 for 43×58). Following the choice/no-choice method that Siegler and I proposed (Siegler & Lemaire, 1997), participants were tested under a choice and two no-choice conditions. In the choice condition, participants could choose between the two rounding strategies to solve each problem. Then, participants were required rounding-up on all problems in one no-choice condition and rounding-down on all problems in the other no-choice condition. Thus, strategy use could be independently investigated in the choice condition and strategy execution in the no-choice condition. Also, all participants were tested under a load and a no-load conditions. In the no-load condition, participants accomplished only the computational estimation task. In the load condition, the executive components of WM were taxed with a choice-reaction time (CRT) task while participants were accomplishing the computational estimation task. For this CRT task, participants had to decide whether randomly presented tones are high or low (Szmalec, Vandierendonck, & Kemps, 2005).

The data revealed two sets of interesting findings, one each for strategy use and strategy execution. As can be seen from Figure 6, participants tended to be less adaptive in their strategy use when their WM resources were taxed. They used the best strategy (i.e., the strategy that yielded the closest product from correct product, like rounding down to solve problems such as 42×8 or rounding up to solve problems like 37×9) less often under WM-load condition, compared to no-load condition. In fact, they were less adaptive because they used the simpler, rounding-down strategy more often under the WM-load condition. This makes sense if using the more complex strategy and using the best strategy on each problem is resource consuming. When part of these resources is captured by a secondary task, participants could choose the best strategy less often. The second set of results concerns strategy execution. As shown in Figure 7, participants were slower under WM-load condition, and even more so for the harder, rounding-up strategy than for the simpler, rounding-down strategy. These two sets of findings revealed that executive functions of working memory are involved in arithmetic strategy use and strategy execution (see also Duverne, Lemaire, & Vandierendonck, 2008).

Strategy-switch costs in arithmetic. We recently adopted another approach to determine whether executive functions are involved in arithmetic strate-

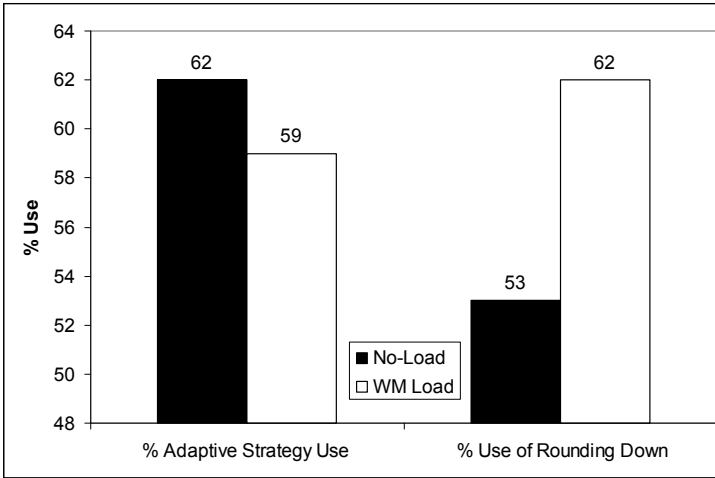


Figure 6

Data showing that participants selected the best strategy on a given problem less often when their WM resources were taxed. They were less adaptive because they tended to use the simpler rounding-down strategy more often (data from Imbo et al., 2007)

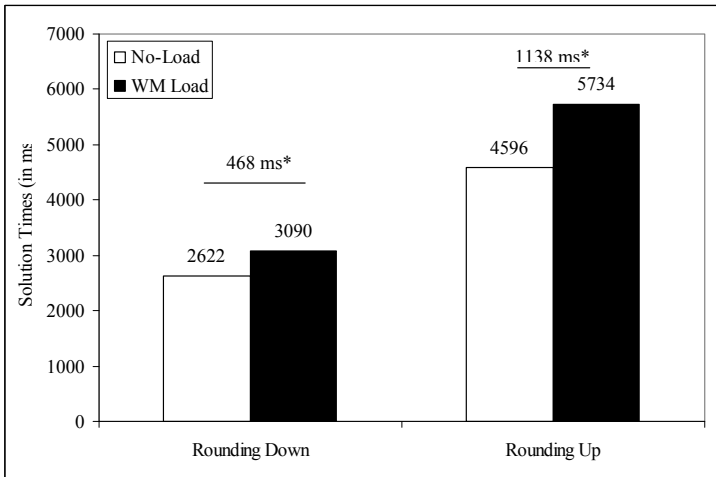


Figure 7

Data showing that loading working-memory led participants to execute strategies more slowly, the harder, rounding-up strategy even more than the easier, rounding-down strategy while participants were accomplishing computational estimation task under a WM-load and a no-load conditions (data from Imbo et al., 2007)

gic variations (Lemaire & Lecacheur, 2010a). In a series of experiments, participants were asked to accomplish computational estimation tasks. On each problem, they were told which strategy to use (again rounding-down vs. rounding-up strategy). Participants were asked to use the same strategy on the two successive problems in half the trials and to use two different strategies in the other trials. As can be seen from Figure 8, participants obtained better performance when they were asked to repeat the same strategy on two consecutive problems than when they were asked to use different strategies. These strategy-switch costs were found only when participants switched from the harder, rounding-up strategy to the easier, rounding-down strategy, and not when they did the reverse. Such findings of asymmetrical switch costs parallel findings from the task-switching literature in which André and his collaborators have recently made several important contributions (e.g., Liefoghe, Demanet, & Vandierendonck, 2009; in press). The present study shows that they do generalize to the case of strategy execution. In another experiment, when participants were free to choose strategies on each problem, we found that they tended to repeat the same strategy on 59% of the problems (Lemaire & Lecacheur, 2010a, Expt. 3). Such strategy switch costs can be explained like task switch costs as resulting in part from executive control processes (i.e., when selecting or executing a new strategy on a problem,

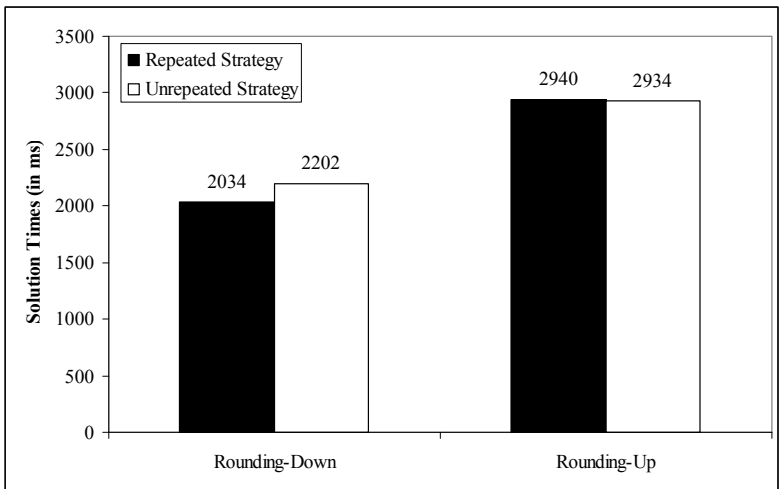


Figure 8

Data showing that participants are faster when they use the same strategy on two consecutive problems than when they use different strategies, and this only when they switch from the harder, rounding-up strategy to the easier, rounding-down strategy. No strategy-switch costs were observed when they switch from the easier to the harder strategy (data from Lemaire & Lecacheur, 2010)

participants have to inhibit the just executed strategy and activate the new strategy, two processes that are not necessary in the repeated strategy condition; see Vandamme, Szmalec, Liefoghe, & Vandierendonck, in press, for ERP data on this). Strategy switch costs have also been recently found while participants accomplish numerosity judgment tasks (Luwel, Schillemans, Onghena, & Verschaffel, 2009). Above and beyond generalizing switch costs to cognitive entities like strategies, these strategy switch costs are important because none of the computational models of strategy selection (e.g., SCADS* model proposed by Siegler and Araya, 2005) assume that strategy selection and strategy execution on a given problem are influenced by the strategy that participants used on the previous problem. None of them assume such executive processes as strategy set reconfiguration that may be at stake in strategy switch costs.

In sum, we have run a set of studies that show that one particular cognitive domain, arithmetic, involves executive functions of working memory. The role of WM/EF has been shown on both participants' performance as well as on how this performance arises (i.e., strategies). Such WM/EF processes have not been envisaged by theories of arithmetic or theories of strategies. Our findings, together with others' such as those published by André and his collaborators, point to the need to revise theories of arithmetic and strategies.

WM/EF and strategic development in arithmetic

Both lines of research, strategic development and the role of WM/EF in arithmetic, have been combined in some of our (and others') studies. The specific issue was whether age-related changes in WM/EF influence strategic development and, if yes, to what extent. Several studies have already been conducted on this issue.

Imbo and Vandierendonck (2007) asked fourth, fifth, and sixth graders to solve one-digit addition problems with the choice/no-choice method (Siegler & Lemaire, 1997). On each problem, participants could choose one of three available strategies: retrieval (i.e., directly retrieving the correct sum from LTM), transforming (i.e., transforming the problem by making an intermediate step to 10, like doing $9+1=10+5$ to solve $9+6$), and counting (i.e., counting subvocally by one until correct sum is reached, like doing $9+1+1+1+1$ to solve $9+4$). Moreover, participants were tested under a no-load condition (i.e., participants only solved arithmetic problems) and under a load condition (i.e., participants were asked to categorize low and high randomly displayed tones while solving arithmetic problems). The goal was to determine whether strategy use is affected by working-memory load and, if yes, whether such effect would change with age. The data, summarized in Figure 9 for fourth and

sixth graders, show no changes in strategy distribution when WM was overloaded with a secondary task. For example, we can see that in fourth graders, participants used the retrieval strategy on 46% and 48% of problems in the no-load and WM-load conditions, respectively. Similarly, sixth graders used it on 60% of problems in both working-memory conditions. In other words, above and beyond increase with age of mean percent use of the retrieval strategy, loading working memory made no differences in these age-related changes (the same findings came out for the other two strategies). This is surprising and may stem from different factors (e.g., the secondary, CRT, task used under the WM-load condition may have not taxed WM resources enough). Recent findings suggest that age-related differences in WM/EF contribute to age-related differences in strategy use.

Barrouillet and Lépine (2005) asked third and fourth graders to solve single-digit addition problems (e.g., 4+7). Of particular interest were frequencies with which participants use the retrieval strategy. They compared children with high working-memory spans and children with low working-memory spans. They found that mean percent use of retrieval correlated more highly with memory span in fourth graders ($r=.31$) than in third graders ($r=.21$). Note however that (a) mean percent use of retrieval did not increase in fourth graders (67%) compared to third graders (65%), and (b) correlations between mean percent retrieval and working-memory spans were not significant on large problems

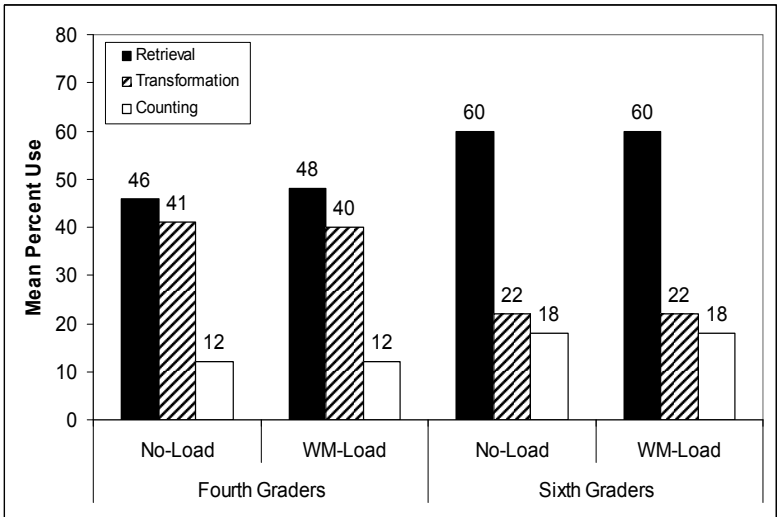


Figure 9

Data showing that there were no differences between load and no-load conditions in strategy distributions in fourth and sixth grade children (data from Imbo & Vandierendonck, 2007)

($r_s=.11$ and $.18$ in third and fourth graders, respectively) but was significant on small problems ($r_s=.35$ and $.41$ in third and fourth graders, respectively). These data suggest that, in children, strategy use and WM/EF are correlated. However, one limitation of these data is that they did not enable to determine whether age-related changes in WM/EF affect age-related changes in strategy selection.

In a recent study, Lemaire and Lecacheur (2010b) asked third, fifth, and seventh graders to select the best strategy for estimating sums to problems like $36+78$. They were asked to choose on each problem one of two available strategies, rounding-down (e.g., doing $30+70$) or rounding-up (doing $40+80$). For $36+78$, rounding-up is the best strategy as it yields the sum (i.e., 120) that is closest from correct sum (i.e., 114). Problems were devised so that half the problems were best solved with the rounding-down strategy (e.g., $32+64$) and half with the rounding-up strategy (e.g., $58+67$), and so that selection of the best strategy was fairly easy (i.e., unit of both operands were smaller or larger than 5 like in $32+54$ and $58+67$) or less easy (i.e., unit digit was smaller than 5 in one operand and larger than 5 in the other operand, like in $34+78$). Children's executive functions were also assessed with neuropsychological tests of EFs (i.e., Stroop, TMT, and Excluded Letter Fluency). Data showed two interesting sets of findings. First, as children grew older, they were more and more able to select the best strategy on each problem. Indeed, seventh graders selected the best strategy on 80% of the problems, fifth graders did it on 75% of the problems, and third graders did it on 65% of the problems. Moreover, mean percent use of the best strategy on each problem correlated significantly with all measures of EFs as well as with composite executive score. When Lemaire and Lecacheur ran hierarchical regression analyses to investigate the extent to which EFs accounted for age differences in mean percent use of the best strategy, they found that the proportion of age-related variance decreased by 67% (from $R^2=.18$ to $R^2=.06$) after control of executive functions. This result suggests that age-related growth in EFs contributes significantly to improvement with age in children's strategy selection. Note that age still had a significant effect after partialling out effects of EFs. This means that EFs do not fully explain age-related differences in strategy selection. As Lemaire and Lecacheur did not include a no-choice condition (i.e., a condition in which participants are required to use a strategy on all items), they could not assess whether age-related differences in EFs influence also strategy execution, which some future project should examine.

In summary, some data suggest that effects of WM/EFs on arithmetic development are mediated by strategic variations. As they grow older and more skilled at arithmetic, children are able to not only execute available arithmetic strategies more efficiently, but they are also able to more and more frequently select the best strategy on each problem. This skill of strategy selection is influenced by WM/EFs, so is its age-related changes.

Conclusions

Studies in arithmetic aim at examining the determiners of arithmetic performance in both adults and children. This enables researchers to decipher underlying cognitive processes so as to explain intra-individual (i.e., condition-related) and inter-individual (i.e., person-related) differences. To pursue this goal, a specific attention has been devoted to strategic aspects of participants' performance. The type of strategies that people use, how they select them and execute them on each problem are crucial determiners of participants' performance. Findings from arithmetic do generalize easily to other cognitive activities which would be fruitfully investigated with a strategy perspective. Similarly, arithmetic performance is influenced by general cognitive constraints.

One cognitive constraint that André Vandierendonck and his colleagues have worked hard on concerns WM/EF. Some of André's works, and others' in both Europe and North America, looked at the role of WM/EF on arithmetic performance and arithmetic strategies. André's specific and most valuable contributions were to first look at this issue from the architecture of WM proposed by Baddeley (using the dual-task methodology to examine components of WM), second to try to specifically investigate the role of EFs of WM (using some targeted secondary task like his CRT tasks and variants), and third to test different populations under different conditions. I illustrated his (and ours) works here with children. However, André and his collaborators made equally valuable contributions when they examined other sources of individual differences such as skills or gender differences. The success of this approach could easily extend to other populations. We used it to address cognitive aging issues (e.g., Gandini, Lemaire, & Dufau, 2008; Lemaire & Arnaud, 2008; Lemaire, Arnaud, & Lecacheur, 2004); but it could be used to investigate specific pathological populations including ADHD children, Alzheimer's patients, or dyscalculic adults or children. One of the great merits of the perspective that André has developed is to make possible and fruitful the combination of both traditional mainstream cognitive psychology (that searches for mechanistic accounts of participants' performance) approach and approaches that showed how important it is to understand functional architecture of the cognitive system in general, and working memory or executive functions in particular. No doubt that future research will continue to benefit a great deal from such combination.

References

- Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8). London: Academic Press.
- Barrouillet, P., & Lépine, R. (2005). Working memory and children's use of retrieval to solve addition problems. *Journal of Experimental Child Psychology*, *91*, 183-204.
- Campbell, J.I.D., & Xue, Q. (2001). Cognitive arithmetic across cultures. *Journal of Experimental Psychology: General*, *130*, 299-315.
- De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and the central executive involved? *Revue d'Intelligence Artificielle*, *29*, 267-274.
- DeStefano, D., & LeFevre, J. A. (2004). The role of working memory in mental arithmetic. *Journal of Cognitive Psychology*, *16*(3), 353-386.
- Duverne, S., & Lemaire, P. (2005). Aging and arithmetic. In J. I. D. Campbell (Ed.), *The Handbook of Mathematical Cognition* (pp. 397-412). New York: Psychology Press.
- Duverne, S., Lemaire, P., & Vandierendonck, A. (2008). Do working-memory executive components mediate the effects of age on strategy selection? Insights from arithmetic problem solving. *Psychological Research-Psychologische Forschung*, *72*(1), 27-38.
- Gandini, D., Lemaire, P., & Dufau, S. (2008). Older and young adults' strategies in approximate quantification. *Acta Psychologica*, *129*(1), 175-189.
- Gandini, D., Lemaire, P., Anton, J.L., & Nazarian, B. (2008). Neural correlates of approximate quantification strategies in young and older adults: An fMRI study. *Brain Research*, *1246*, 144-157.
- Imbo, I., Duverne, S., & Lemaire, P. (2007). Working memory, strategy execution, and strategy selection in mental arithmetic. *Quarterly Journal of Experimental Psychology*, *60*(9), 1246-1264
- Imbo, I., & Vandierendonck, A. (2007). The development of strategy use in elementary-school children: Working memory and individual differences. *Journal of Experimental Child Psychology*, *96*, 284-309.
- LeFevre, J.-A., Bisanz, J., Daley, K.E., Buffone, I., Greenham, S.L., & Sadesky, G.S. (1996a). Multiple routes to solution of single-digit multiplication problems. *Journal of Experimental Psychology: General*, *125*, 284-306.
- LeFevre, J.-A., Sadesky, G.S., & Bisanz, J. (1996a). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *22*, 216-230.
- LeFevre, J. A., DeStefano, D., Coleman, B., & Shanahan, T. (2005). Mathematical cognition and working memory. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition*. New York: Psychology Press.
- Lemaire, P., Abdi, H., & Fayol, M. (1996). The role of working memory resources in simple cognitive arithmetic. *European Journal of Cognitive Psychology*, *8*(1), 73-103.
- Lemaire, P., & Arnaud, L. (2008). Young and older adults' strategies in complex arithmetic. *American Journal of Psychology*, *121*(1), 1-16

- Lemaire, P., Arnaud, L., & Lecacheur, M. (2004). Adults' sage-related differences in adaptivity of strategy choices: Evidence from computational estimation. *Psychology and Aging, 10*(3), 467-481.
- Lemaire, P., & Calliès, S. (2009). Children's strategies in complex arithmetic. *Journal of Experimental Child Psychology, 103*, 49-65.
- Lemaire, P., & Fayol, M. (1995). When plausibility judgments supersede fact retrieval: The example of the odd^even effect on product verification. *Memory and Cognition, 23*(1), 34-48.
- Lemaire, P., & Lecacheur, M. (2010a). Strategy switch costs in arithmetic problem solving. *Memory and Cognition, 38*, 322-332.
- Lemaire, P., & Lecacheur, M. (2010b). Age-related changes in children's executive functions and strategy selection: A study in computational estimation. (Revision under review)
- Lemaire, P., & Reder, L. (1999). What affects strategy selection in arithmetic? An example of parity and five effects on product verification. *Memory & Cognition, 22*, 364-382.
- Liefooghe, B., Demanet, J., & Vandierendonck, A. (2009). Is advance reconfiguration in voluntary task switching affected by the design employed? *Quarterly Journal of Experimental Psychology, 65*, 850-857.
- Liefooghe, B., Demanet, J. & Vandierendonck, A. (in press). Selecting tasks of unequal strength. *Psychonomic Bulletin & Review*.
- Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.
- Siegler, R. S., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. In R. V. Kail (Ed.), *Advances in child development and behaviour* (pp. 1-42). Oxford, UK: Elsevier.
- Siegler, R. S., & Lemaire, P. (1997). Older and younger adults' strategy choices in multiplication: Testing predictions of ASCM using the choice/no-choice method. *Journal of Experimental Psychology: General, 126*(1), 71-92.
- Szmalec, A., Vandierendonck, A., & Kemps, A. (2005). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition, 33*, 531-541.
- Vandamme, K., Szmalec, A., & Liefooghe, B., & Vandierendonck, A. (in press). Are voluntary switches corrected for repetitions? *Psychophysiology*.
- Vandorpe, S., De Rammelaere, S., & Vandierendonck, A. (2004). The odd-even effect in multiplication: Familiarity with even numbers or a parity rule after all? *Psychologica Belgica, 44*, 143-157.