Age-related changes in strategic variations during arithmetic problem solving: The role of executive control

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Abstract

In this review, we provide an overview of how age-related changes in executive control influence aging effects in arithmetic processing. More specifically, we consider the role of executive control in strategic variations with age during arithmetic problem solving. Previous studies found that age-related differences in arithmetic performance are associated with strategic variations. That is, when they accomplish arithmetic problem-solving tasks, older adults use fewer strategies than young adults, use strategies in different proportions, and select and execute strategies less efficiently. Here, we review recent evidence, suggesting that age-related changes in inhibition, cognitive flexibility, and working memory processes underlie age-related changes in strategic variations during arithmetic problem solving. We discuss both behavioral and neural mechanisms underlying age-related changes in these executive control processes.

Keywords

Strategies, Arithmetic, Aging, Executive control, Sequential modulations

Research in arithmetic aims at determining how participants find the correct answers of problems like 8×7 or determine whether an equation like $8 \times 7 = 46$ is true or false. Several decades of research revealed that arithmetic performance and age-related differences therein are determined by the type of strategies that participants use (see Duverne and Lemaire, 2005; Lemaire, 2015; Siegler, 2007; Uittenhove and Lemaire, 2014 for reviews). The term "strategy" usually refers to "a procedure or a set of procedures for achieving a higher level goal or task" (Lemaire and Reder, 1999, p. 365). Thus, adopting a strategy perspective allows to account for participants' performance in terms of mechanisms, together with age-related changes in

performance. Strategic variations with age were found to result in older adults using fewer strategies than young adults, using available strategies in different proportions, and selecting and executing strategies less efficiently. Until recently, unknown were the mechanisms underlying these age-related changes in strategic aspects of arithmetic problem performance. However, recent works started to decipher these mechanisms. In particular, recent findings suggest that executive control mechanisms have a crucial role.

The main goal of this review is to discuss the role of executive control processes in age-related changes in strategic variations during arithmetic problem solving. We first briefly summarize age-related changes in arithmetic performance and strategic variations with age during arithmetic problem solving. Then, we review correlational, experimental, and brain imaging data to discuss the contribution of executive control processes in age-related changes in strategy repertoire, selection, and execution, when participants accomplish arithmetic problem-solving tasks. These findings are important, as they shed light on cognitive processes involved in arithmetic problem solving, and how these processes change with age during adulthood.

1 AGE-RELATED DIFFERENCES DURING ARITHMETIC PROBLEM SOLVING

1.1 AGING EFFECTS ON ARITHMETIC PERFORMANCE

Research has documented several age-related changes in arithmetic performance (see Duverne and Lemaire, 2005; Uittenhove and Lemaire, 2014 for reviews). When asked to solve arithmetic problems, older adults were found to compute exact products of problems more slowly and less accurately than young adults. These age-related differences in computation also increase as a function of problem complexity. As an example, Salthouse and Coon (1994) asked participants to solve complex arithmetic problems with several operations (eg, $5+3-1-(3+4)-1=6$, TRUE? FALSE?). Salthouse and Coon found that older adults were slower than young adults to solve problems, and that differences between young and older adults were larger when problems involved seven operations as compared to three operations (see also Allen et al., 1992; Charness and Campbell, 1988; Geary and Wiley, 1991). Computation implies multiple processes, including retrieval, maintenance of problem structure, and integration of partial results to calculate correct products (eg, Trbovich and LeFevre, 2003). Moreover, these processing costs are larger when problems involve more operations.

When available, problems can also be solved by means of arithmetic fact retrieval. Arithmetic fact retrieval refers to direct recall of the correct products from long-term memory. In comparison to computation, arithmetic fact retrieval involves fewer procedures and depends more on past experience (eg, Geary et al., 1996; Koshmider and Ashcraft, 1991; Lemaire et al., 1994).

Regarding aging effects, older adults were found to be slower than young adults to retrieve arithmetic facts from memory, although they remain as accurate as young adults (eg, Allen et al., 1992, 1997; Geary and Wiley, 1991; Thevenot et al., 2013). Moreover, older adults were found to use retrieval more often than young adults (Geary and Wiley, 1991; Geary et al., 1993; Thevenot et al., 2013). More interestingly, Thevenot et al. (2013) found that greater reliance on retrieval strategy sometimes allows older adults to obtain as good performance as young adults when asked to solve arithmetic problems. These findings can be the result of older adults having more experience of arithmetic problem solving than young adults, thereby benefiting from a larger and more developed arithmetic fact network.

1.2 STRATEGIC VARIATIONS WITH AGE IN ARITHMETIC

To solve arithmetic problems, participants can use a wide variety of strategies. Age-related differences in strategy repertoire consist in differences in the number and/or the type of strategies used by young and older adults. As an example, Hodzik and Lemaire (2011) collected verbal reports when participants solved two-digit addition problems and determined that participants used nine different strategies. Indeed, to solve an equation like $17+51$, participants can either (a) use retrieval (eg, 68), (b) round the first operand down (eg, $10+51+7$), (c) round the second operand down (eg, $17+50+1$), (d) round both operands down (eg, $10+50+7+1$), (e) round the first operand up (eg, $20+51-3$), (f) round the second operand up (eg, $17+60-9$), (g) round both operands up (eg, $20+60-3-9$), (h) use columnar retrieval (eg, $1+5=6$ for the decades, and $7+1=8$ for the units), or (i) borrow units (eg, $18+50$). Hodzik and Lemaire (2011) found that, at the group level, both young and older adults used these nine strategies. However, the mean number of strategies used by individual participants was smaller in older adults (2.1 strategies) compared to young adults (3.0 strategies). This importantly suggest that, even if both age groups know all available strategies, strategy sets used in a given task are smaller in older adults than in young adults (see also Ardiale et al., 2012; Arnaud et al., 2008; Duverne et al., 2008; El Yagoubi et al., 2005; Hodzik and Lemaire, 2011; Lemaire and Arnaud, 2008).

Of all strategies used by individuals to accomplish cognitive tasks, some strategies are used more frequently and other strategies are used less frequently. Young and older adults differ in how often they use each available strategy. Age-related changes in strategy distribution mainly consist in a shift toward simpler, less demanding strategies. As an example, Gandini et al. (2008a) studied estimation strategies used to determine numerosity of collections of dots and found age-related changes in strategy distribution. Relative to young adults, older adults used approximate counting strategies (ie, estimating several groups of dots, then adding them) less often than young adults, while benchmark strategy (ie, guessing from visual scanning; eg, "it looks like there is a bit more than 30 dots") was more frequently used in older adults than in young adults. Benchmark strategy was favored in older

adults, most likely because it relies more on long-term memory than other strategies. Indeed, through accumulated experience, long-term memory has become rich and well organized in older adults relative to young adults. It is important to note that age-related changes in strategy distribution are not always related to decreased performance in older adults. Indeed, greater reliance on retrieval strategy to solve simple arithmetic problems is an adapted strategy choice, as this strategy is less demanding and more efficient than other arithmetic strategies (eg, Geary et al., 1996). Moreover, larger use of retrieval strategy sometimes enables older adults' performance to match young adults (eg, Thevenot et al., 2013). This adapted strategy choice in older adults may result from cohort effects (ie, higher formal training and better basic numerical skills for older adults compared to young adults).

Aging effects on strategy selection were investigated by determining whether young and older adults are equally efficient at selecting the best strategy on each problem and at adjusting strategies to several task parameters (eg, instructions, items). In arithmetic, as in other cognitive domains, older adults select the better strategy (ie, which yields the best performance) on each problem less frequently than young adults (eg, Ardiale and Lemaire, 2012, 2013; Green et al., 2007; Hodzik and Lemaire, 2011; Lemaire and Lecacheur, 2010; Lemaire and Leclère, 2014a,b; Lemaire et al., 2004). As an example, Lemaire et al. (2004) asked participants to find approximate products of problems like 46×52 without calculating the exact answer. Participants had to choose between the rounding-down strategy (ie, rounding both operands down to the nearest decades; eg, doing 40×50 to estimate 46×52) or the rounding-up strategy (ie, rounding both operands up to the nearest decades; eg, doing 50×60 to estimate 46×52). These two strategies were selected because the rounding-down strategy is a better strategy when unit digits of both operands are smaller than 5 (or when sums of unit digits are smaller than 10), while the rounding-up strategy is better when unit digits of both operands are larger than 5 (or when sums of unit digits are larger than 10). Older adults were found to select the better strategy less often than young adults.

Strategies can also be characterized by the number and the type of processes they include. Research on age-related changes in strategy execution mainly found that older adults take more time and make more mistakes than young adults when executing arithmetic strategies, especially the most difficult ones (eg, Hinault et al., 2014, 2016; Lemaire et al., 2004; Lemaire and Hinault, 2014; Lemaire and Lecacheur, 2001, 2010; Taillan et al., 2015a; Uittenhove and Lemaire, 2012, 2013a,b; Uittenhove et al., 2013). For example, when comparing young and older adults execution of numerosity estimation strategies, Gandini et al. (2008a) found that older adults were less efficient to execute the anchoring strategy than young adults. The anchoring strategy is assumed to be harder for older adults because it involves several procedures such as decomposing the item sets into smaller groups, subitizing them, and adding the number of similar groups. Similarly, Lemaire et al. (2004) found larger age-related differences, while participants executed the rounding-up strategy relative to the rounding-down strategy to find approximate products in computational estimation tasks.

2 THE ROLE OF EXECUTIVE PROCESSES IN STRATEGIC VARIATIONS WITH AGE IN ARITHMETIC

All in all, research on strategic variations with age in arithmetic revealed that, relative to young adults, older adults use fewer strategies, have different strategy preferences, select the better strategy less often, and execute strategies less efficiently. Recently, while trying to further understand the sources of these strategic variations with age, research discovered that executive control processes are crucial. Executive control processes refer to top-down processes that are involved when automatic processing is not possible, or would be ill-advised (see Diamond, 2013 for a review). Following Miyake et al. (2000), executive control processes are viewed as involving three core processes. *Inhibition* enables to not give an irrelevant answer or to avoid processing information when it is not appropriate. *Cognitive flexibility* is required when switching or alternating between different concepts or representations. *Updating and monitoring of working memory* involves active maintenance of relevant representations and change for new, more appropriate, representations when required. With aging, decline in inhibition (eg, Mayas et al., 2012), cognitive flexibility (eg, Tombaugh, 2004), and working memory (eg, Salthouse, 1994) has been observed. Hence, the hypothesis that such decline may underlie age-related changes in strategic variations was proposed. We next review recent evidence that seem to support this hypothesis. We discuss such evidence for strategy use, selection, and execution separately.

2.1 AGING, EXECUTIVE CONTROL PROCESSES, AND ARITHMETIC STRATEGY USE

Hodzik and Lemaire (2011) observed reduced strategy repertoire in older adults compared to young adults, when investigating the strategies used to estimate two-digit addition problems. Hodzik and Lemaire also wanted to determine whether aging effects on executive control processes could explain this decreased number of strategies with age. Together with an arithmetic task, Hodzik and Lemaire asked participants to perform two executive control tasks, the Trail Making Test (TMT) (Partington and Leiter, 1949; Reitan, 1958) and the Stroop task (Stroop, 1935). The TMT was used to assess cognitive flexibility. It includes two parts, part A (ie, participants have to connect numbers in an ascending order; eg, 1–2–3) and part B (ie, participants have to connect numbers and letters alternatively in an ascending order; eg, 1–A–2–B–3–C). The difference between parts B and A measured the additional costs of having to flexibly switch between two task criteria. Participants also performed the Stroop Color task to assess inhibition capacities. In a color subset, participants had to read color words written in black (eg, the word "*red*" written in black ink). Then, in a color-word interference subset, participants had to indicate the color of words designating colors, without reading the words. Color of words was either congruent with color words (eg, the word

"*red*" written in red) or incongruent with color words (eg, the word "*red*" written in green). Incongruent items require inhibition of the automatic tendency to read words to give the correct answer. Inhibition abilities were evaluated by subtracting the time needed for color-word interference subset from the time needed for color subset.

Results of regression analyses revealed that inhibition and cognitive flexibility mediated 89% and 63%, respectively, of age-related changes in strategy repertoire. These findings importantly revealed that the reduction of strategy repertoire with age is related to less efficient executive control mechanisms. With age, flexibly switching between several strategies, and inhibiting the less appropriate strategies to solve problems are less efficient. As a consequence, older adults may choose to rely on a smaller set of strategies to solve arithmetic problems, because smaller strategy sets make fewer demands on inhibition and cognitive flexibility resources.

2.2 AGING, EXECUTIVE CONTROL PROCESSES, AND ARITHMETIC STRATEGY SELECTION

2.2.1 Correlational data

Recent data suggest that decline in executive control processes also accounts for age-related differences in strategy selection processes. Hodzik and Lemaire (2011) used Stroop and TMT tasks and revealed that executive control processes partly accounted for decreased percent use of the best strategy with age, when participants were asked to find estimates of two-digit multiplication problems. Indeed, regression analyses revealed that inhibition (ie, performance in the Stroop task) and cognitive flexibility (ie, performance in the TMT task) abilities mediated 44% and 39%, respectively, of the age-related reduction in percent use of the best strategy on each problem. This evidence suggests that age-related decrease in inhibition of irrelevant strategies as well as in cognitive flexibility to switch to the better strategy on each problem led older adults to be less adaptive when choosing among several strategies on each problem. Note, however, that mediation analyses also revealed remaining, unexplained variance in decreased use of the best strategy with age. Thus, other factors seem to also be involved in aging effects on strategy adaptiveness, which future research should unravel.

2.2.2 Experimental data

Two experimental effects are consistent with the hypothesis that executive processes are involved in less adaptive strategy selection with age: strategy perseveration effects and within-item strategy switching. Strategy perseveration (eg, Lemaire and Lecacheur, 2010; Luwel et al., 2009; Schillemans et al., 2010, 2011, 2012) refers to the larger tendency to repeat the same strategy over two consecutive problems than to switch for another, sometimes more appropriate strategy. As an example, when asked to select the best strategy (ie, between the rounding-down or the rounding-up strategy) to provide approximate products of two-digit multiplication problems, Lemaire and Leclère (2014a) found that both young and older adults tended to use the same strategy between two consecutive problems, even if the best

strategy was different on these two problems. Furthermore, such strategy persever-ation effects were larger in older adults than in young adults. Strategy switch from one trial to the next involves inhibition of the just-executed, more readily activated strategy; reactivation of the available strategy set; selection of the better strategy among these strategies; and execution of the selected strategy. Efficient inhibition is crucial to flexibly select and execute a better strategy on a given problem, inde-pendently of which strategy was used on the previous problem. Age-related changes in strategy perseveration effects suggest that decreased inhibitory efficiency in older adults (eg, Mayas et al., 2012) leads them to less efficiently switch strategy from one trial to the next.

An additional phenomenon has suggested that executive control influences strategy selection and age-related differences therein. This is the phenomenon of within-item strategy switching. This phenomenon was discovered when Ardiale and Lemaire (2012, 2013) asked participants to estimate products of two-digit mul-tiplication problems with a cued rounding-down or rounding-up strategy. After 1000 ms, participants had to choose between sticking with the cued strategy or changing strategy if they judged that the cued strategy was not the better strategy. The cued strategy was the better for half the problems and the poorer for the other problems. Ardiale and Lemaire found that older adults switched less frequently than young adults for the noncued strategy, even when the noncued strategy was the better strategy. These within-item strategy switching effects were interpreted as reflecting the need to inhibit the already activated strategy mid-execution to switch for the other, more appropriate, strategy (see also Lemaire and Lecacheur, 2010; Taillan et al., 2015a). In older adults, decreased efficiency of inhibitory control processes leads them to less efficiently disengage from the already activated strategy and to stay with the cued strategy.

2.2.3 Brain imaging data

Recent functional magnetic resonance imaging (fMRI) evidence for executive control involvement during strategy selection has been reported by Taillan et al. (2015b). Taillan et al. analyzed fMRI, while participants had to select the better strategy (ie, which yields the closest estimate to the correct product) between rounding-down and rounding-up strategies to accomplish a computational estimation task. Brain activations and performance were compared between a choice condition (ie, participants had to choose between two strategies on all problems) and a no-choice condition (ie, participants had to execute a cued strategy on all problems). In young adults, larger brain activations in the choice condition relative to the no-choice condition were found in anterior cingulate cortex (ACC), dorsolateral pre-frontal cortex (DLPFC), and angular gyrus (ANG). Activations in the right ANG were interpreted as reflecting the focused attention on unit digits when participants had to select the better strategy. The ACC and DLPFC were previously observed in conflict tasks and were interpreted as reflecting response conflict detection and res-olution (eg, Botvinick et al., 2001, 2004; Braver, 2012; Braver et al., 2009; Kerns, 2004, 2006). Similarities of brain activations between conflict tasks and arithmetic

strategy selection are consistent with the involvement of executive control processes in the selection of the better strategy on each problem, in computational estimation tasks. Indeed, executive control processes are necessary during strategy selection to inhibit and disengage from the previously executed strategy, and to choose an alternative strategy on the next problem. For now, no fMRI studies were conducted to investigate age-related changes in brain areas underlying strategy selection.

In summary, aging affects fine calibration of which strategy is used on a given problem. These age-related declines in strategy selection are related to decreased efficiency of executive control processes. Indeed, recent results suggest that the ability to inhibit poorer strategies and to flexibly switch strategies from one trial to the next declines with age. Decline in executive control processes leads older adults to more frequently repeat the same strategy over consecutive trials, and to select and execute irrelevant strategies more often than young adults.

2.3 AGING, EXECUTIVE CONTROL PROCESSES, AND ARITHMETIC STRATEGY EXECUTION

Recent effects suggest that strategy execution also involves executive control processes, and that age-related decreased efficiency in executive control processes contributes to age-related differences in strategy execution. These effects are strategy switch costs, strategy sequential difficulty effects, and sequential modulations of poorer strategy effects.

2.3.1 Strategy switch costs

When asked to execute a cued strategy on each problems, Lemaire and Lecacheur (2010) found that participants were faster and more efficient when the same strategy was cued on two successive problems than when two different strategies were required (see also Lemaire and Brun, 2014). Moreover, Ardiale et al. (2012) found increased strategy switch costs in older adults compared to young adults (see Fig. 1). These strategy switch costs share similarities with task switch costs reported in the literature on executive control (eg, Vandierendonck, 2016; see Meiran, 2010; Vandierendonck et al., 2010 for reviews). Indeed, after executing a strategy on a problem, participants had to inhibit this just-executed strategy to be able to switch for another strategy on the next problem, if required. These additional mechanisms, inhibition and cognitive flexibility, are not needed when the same strategy is cued on two successive problems, resulting in shorter latencies. Age-related differences in strategy switch costs are consistent with older adults being less efficient to inhibit the just-executed strategy, and less likely than young adults to switch for a new strategy. However, as discussed in detail by Lemaire and Lecacheur (2010), it is important to note that strategy switch costs may also differ from switch costs observed in task-switching research. Indeed, in contrast to task-switching research (eg, see Meiran, 2010; Vandierendonck et al., 2010, for reviews), updating of goal representations is not needed during strategy switching, as only the strategy has to be replaced to another strategy.
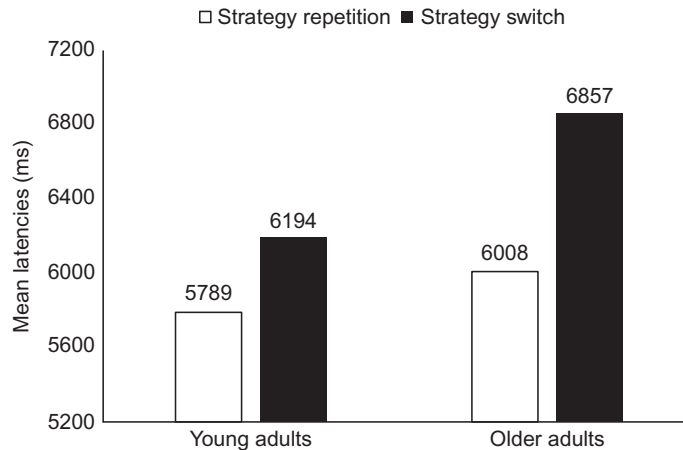
FIG. 1

Mean solution latencies on current problems (in ms) as a function of whether participants had to switch or to repeat strategy from previous to current problems, in young and older adults. Older adults showed larger strategy switch costs than young adults.

Data from Ardiale, E., Hodzik, S., Lemaire, P., 2012. Aging and strategy switch costs: a study in arithmetic problem solving. Annee Psychol. 112 (03), 345–360. http://dx.doi.org/10.4074/S0003503312003028.

2.3.2 Strategy sequential difficulty effects

Trial-to-trial modulations of strategy execution do not only occur as a function of strategy switch or strategy repetition on two successive problems. Sequential modulations of strategy execution can also occur based on the difficulty of the previously executed strategy. Indeed, strategy sequential difficulty effects refer to better performance to execute a strategy on a given problem after executing an easier strategy on the immediately preceding problem, compared to following a harder strategy (Uittenhove and Lemaire, 2012, 2013a,b, 2014; Uittenhove et al., 2013). Uittenhove and Lemaire (2012) asked participants to estimate products of two-digit addition problems with a cued mixed-rounding strategy (ie, rounding the first operand down to the nearest decade and the second operand up to the nearest decade; eg, doing 40+30 to estimate 43+28). The immediately preceding problem was cued either with a rounding-down strategy or with a rounding-up strategy. These three strategies were selected because rounding-down strategy is easier than rounding-up strategy (ie, involving additional steps to increment decades), while mixed-rounding strategy is of medium difficulty. Uittenhove and Lemaire (2012) found that participants had poorer performance with the mixed-rounding strategy on a given problem when following the harder, rounding-up strategy compared to after the easier, rounding-down strategy. Furthermore, the magnitude of these strategy sequential difficulty effects was significantly correlated with individuals' working memory capacities (Uittenhove and Lemaire, 2013a). Interestingly, comparable strategy sequential

☐ Previous problems: rounding-down strategy
■ Previous problems: rounding-up strategy
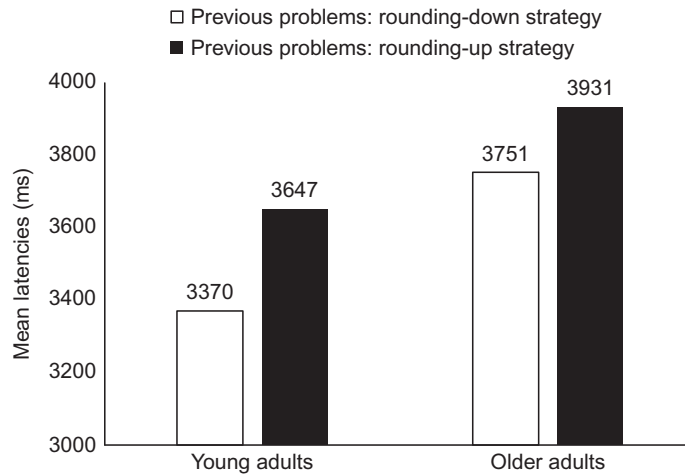
FIG. 2

Mean solution latencies on current problems (in ms), solved with the mixed-rounding strategy as a function of the strategy that was executed on the immediately preceding problems, in young and older adults. Older adults showed similar strategy sequential difficulty effects to young adults.

Data from Ardiale, E., Hodzik, S., Lemaire, P., 2012. Aging and strategy switch costs: a study in arithmetic problem solving. Annee Psychol. 112 (03), 345–360. http://dx.doi.org/10.4074/S0003503312003028.

difficulty effects were found in young and older adults (see Fig. 2; Uittenhove and Lemaire, 2013b). These effects were interpreted as resulting from harder, rounding-up strategy being more demanding on working memory processes than easier, rounding-down strategy. On the current problems, participants had fewer working memory resources available for the execution of the mixed-rounding strategy after the rounding-up relative to following the rounding-down strategy. Regarding age invariance in strategy sequential difficulty effects, it was proposed that working memory processes were preserved or not sufficiently affected to yield larger strategy sequential difficulty effects in older adults.

Analyses of ERP data brought additional evidence for the hypothesis that working memory processes are crucial in strategy sequential difficulty effects. Uittenhove et al. (2013) found a larger anterior left negativity on current problems solved with the mixed-rounding strategy, between 200 and 550 ms, after executing the rounding-up strategy relative to following the rounding-down strategy. These negativity were observed over anterior left sites of the scalp, suggesting an involvement of executive control, as anterior left sites were frequently found to be activated in conflict tasks (eg, Kane and Engle, 2003). Moreover, findings are consistent with N450 (ie, fronto-central negativity occurring between 350 and 500 ms after stimulus onset), recently observed in both conflict (eg, West et al., 2012) and arithmetic (eg, Suárez-Pellicioni et al., 2014) tasks, and associated with controlled processing

(eg, Szűcs and Soltész, 2012). This N450 could then reflect increased difficulty to retrieve and execute strategy procedures following execution of the harder strategy. Note that no research has yet been conducted to determine whether young and older adults differ in electrophysiological activities associated with strategy sequential difficulty effects.

2.3.3 Sequential modulations of poorer strategy effects

Recently discovered, poorer strategy effects and sequential modulations of poorer strategy effects (Hinault et al., 2014, 2016; Lemaire and Hinault, 2014) also suggest that strategy execution requires executive control processes. Poorer strategy effects refer to longer latencies and larger error rates when participants are required to use a poorer strategy compared to when they are asked to execute the better strategy (Ardiale et al., 2012; Hinault et al., 2014, 2016; Lemaire and Hinault, 2014). These poorer strategy effects are larger in older adults than in young adults (Lemaire and Hinault, 2014). Poorer strategy effects were assumed to result from the need to inhibit the more readily activated better strategy to activate and execute the cued, poorer strategy on poorer strategy problems. Thus, latencies and error rates are larger compared to when the better strategy is required, and that these additional control processes are not needed. With age, effects were assumed to reflect less efficient inhibition of the automatic tendency to use the better strategy.

Research on arithmetic strategies revealed that poorer strategy effects on a given problem were sequentially modulated as a function of the strategy executed on the immediately preceding problem. Indeed, poorer strategy effects on a given problem decreased following execution of the poorer strategy compared to after executing the better strategy on the immediately preceding problem. These sequential effects were interpreted as reflecting the higher level of control following execution of the poorer strategy being maintained from one trial to the next. Conversely, inhibitory processes are less activated (or not even involved) following the execution of the better strategy, which leads to larger poorer strategy effects on the next problem. Sequential modulations of poorer strategy effects bear important similarities with congruency sequence effects previously found in conflict tasks (Gratton et al., 1992). In conflict tasks, congruency effects (see Hommel, 2011; Lu and Proctor, 1995 for reviews) refer to poorer performance on incongruent items (ie, stimulus irrelevant and relevant dimensions are different; eg, in a Stroop task, the word "*red*" is written in green) relative to congruent items (ie, stimulus irrelevant and relevant dimensions are the same; eg, in a Stroop task; the word "*red*" is written in red). Congruency sequence effects refer to reduced congruency effects on a given item after an incongruent item relative to following a congruent item. These effects were interpreted as resulting from trial-to-trial modulations of top-down control processes (Botvinick et al., 2001; De Pisapia and Braver, 2006; see Duthoo et al., 2014; Scherbaum et al., 2012 for alternative views). Finding similar patterns of sequential modulations in both arithmetic and conflict tasks suggests similar sequential modulations of executive control processes involved.

Aging effects on sequential modulations of poorer strategy effects could contribute to less efficient execution of arithmetic strategies in older adults. With aging, an overall decline in sequential modulations of poorer strategy effects was observed (Lemaire and Hinault, 2014). In older adults, Lemaire and Hinault found increased poorer strategy effects after execution of the poorer strategy on the previous problem compared to following execution of the better strategy, in complete contrast to young adults. These reversed sequential modulations of poorer strategy effects in older adults were interpreted as reflecting strategy sequential difficulty effects (ie, carryover effects of difficult, resource-consuming conditions, to the next items). With fewer available resources, older adults were unable to prepare themselves to process poorer strategy problems following poorer strategy problems, because previous poorer strategy problems consumed most of their available resources. Interestingly, Lemaire and Hinault found important individual differences in older adults' sequential modulations of poorer strategy effects, with a group of older adults showing the same pattern as young adults and another group of older adults showing reversed sequential modulations of poorer strategy effects (see Fig. 3). Interestingly, the former showed higher level of congruency sequence effects in an executive control, Simon task (ie, conflict task that requires to inhibit a spatial dimension to focus on a target dimension, for example, the shape; Simon and Small, 1969),
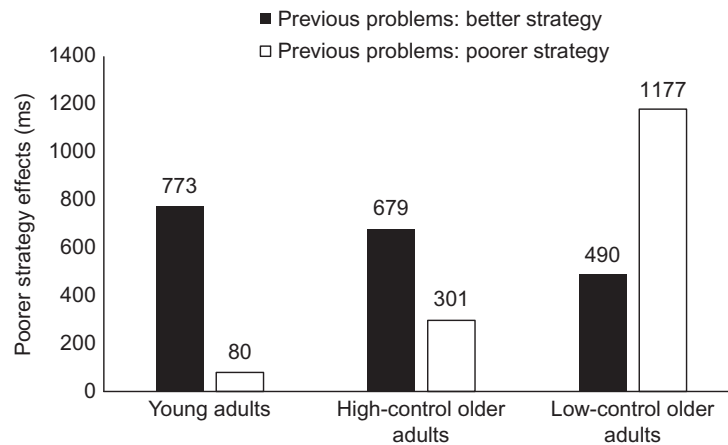

FIG. 3

Poorer strategy effects as a function of previous better strategy problems vs poorer strategy problems, in young adults, high-control older adults, and low-control older adults. High-control older adults showed similar sequential modulations of poorer strategy effects to young adults, while low-control older adults showed reversed sequential modulations of poorer strategy effects.

Data from Lemaire, P., Hinault, T., 2014. Age-related differences in sequential modulations of poorer-strategy effects. Exp. Psychol. 61 (4), 253–262. http://dx.doi.org/10.1027/1618-3169/a000244.

whereas the latter showed lower levels of sequential modulations of congruency effects. In other words, older adults who showed sequential modulations of poorer strategy effects were high-control older adults (ie, older adults whose executive control processes were efficient), whereas older adults who showed reversed sequential modulations of poorer strategy effects were low-control older adults (ie, older adults whose executive control processes were much less efficient).

Interestingly, electrophysiological signatures of sequential modulations of poorer strategy effects were found (Hinault et al., 2014), as well as aging effects on these electrophysiological signatures (Hinault et al., 2016). Hinault and colleagues found that, in young adults, sequential modulations of poorer strategy effects were associated with modulations of ERPs in early and late time windows, over anterior left sites of the scalp. Modulations of ERPs in the first time window (ie, 200–550 ms after stimulus presentation) were interpreted as reflecting control mechanisms engaged immediately after the encoding of the problem, to focus on the cue and inhibit the automatic activation of the better strategy. The second time window (ie, 850–1250 ms following stimulus display) was assumed to reflect participants keeping the activation of the better strategy at its lower level while executing the required poorer strategy. EEG allowed to determine that latencies and topographies of modulations share similarities with ERP components elicited by congruency sequence effects (see Larson et al., 2014 for a review). Indeed, modulations were consistent with P3 (ie, positivity occurring around 300 poststimulus presentation) and conflict SP (ie, sustained positivity starting about 500 ms following stimulus display) components. In conflict tasks, these components were interpreted as reflecting inhibition of automatic tendencies (ie, P3) and engagement of additional executive control processes (ie, conflict SP). These similarities suggest that performance in computational estimation tasks can be modulated by similar control processes to those involved in conflict tasks.

In a subsequent study, Hinault et al. (2016) aimed at understanding how high-control older adults showed similar behavioral sequential modulations of poorer strategy effects than young adults. Both groups were matched on behavioral performance. Results revealed that high-control older adults showed, like young adults, early and later sets of executive control processes. However, modulations occurred earlier in older adults than in young adults, first between 0 and 200 ms, and then between 550 and 850 ms (compared to 200–550- and 850–1250-ms windows in young adults). Age-related differences were interpreted as reflecting larger preparation in older adults to reach similar behavioral performance relative to young adults. Indeed, in conflict tasks, executive control processes have been observed to occur as early as 100 ms after stimulus presentation (eg, Shedden et al., 2013). Moreover, later modulations have been associated with N450 (ie, fronto-central negative deflection elicited about 400–550 ms following stimulus presentation), associated with implementation of executive control processes (eg, Larson et al., 2014). Findings of earlier modulations in older adults than in young adults are consistent with a study of high-control older adults, who were able to proactively prepare themselves to a greater extent than young adults to process a potential conflict, and to maintain behavioral

performance similar to young adults. In addition to analysis on ERPs data, Hinault et al. (2016) also conducted time–frequency and coherence analyses to investigate qualitative differences between young adults and high-control older adults. They found that, relative to young adults, older adults showed larger power in the delta band (1–3.5 Hz), together with interhemispheric theta (4–8 Hz) coherence. These frequency bands were previously associated with healthy cognitive aging (eg, Finnigan and Robertson, 2011). Therefore, Hinault et al. proposed to consider these age-related differences as neurophysiological markers of high-performing older adults, allowing them to show similar behavioral performance than young adults.

In summary, relative to young adults, older adults showed declined ability to efficiently execute arithmetic strategies. Age-related decline in strategy execution is related to less efficient executive processes with age. Indeed, recent experimental effects demonstrated that older adults are less efficient to (a) execute two different strategies on two successive problems and (b) prepare themselves, after the execution of a poorer strategy, to more efficiently execute a cued strategy on the next problem. These age-related changes were related to decline in inhibitory and cognitive flexibility processes. With age, it becomes harder to flexibly execute different strategies on successive problems and to maintain activated inhibitory processes from one problem to the next. However, important individual differences can be found in older adults, with some older adults showing as efficient sequential modulations of executive control processes as young adults, and others being significantly impaired.

3 CONCLUSIONS AND FUTURE DIRECTIONS

This review aimed at highlighting the role of executive control processes in age-related changes during arithmetic problem solving. In comparison to young adults, older adults use fewer strategies, use available strategies in different proportions, select the best strategy on each problem less frequently, and execute strategies less efficiently. Recent data are consistent with the hypothesis that decline in executive control processes influences these strategic variations with age in arithmetic. With age, inhibition of the tendency to use a noncued or nonappropriate strategy to use a better strategy is less efficient. Also, switching from a just-executed strategy to another strategy is harder. Moreover, sequential effects emerge from less efficient inhibitory control and maintenance of strategies in working memory from one trial to the next, and these sequential effects decrease with age in some older adults.

All in all, research documented many effects consistent with the hypothesis that executive control processes influence strategy repertoire, selection, and execution. However, no studies were conducted to investigate whether executive control processes are also involved in strategy distribution, and in age-related differences in this strategy dimension. Future research will determine whether changes in inhibition, cognitive flexibility, and working memory processes contribute to age-related differences in strategy distribution. Indeed, older adults differ from young adults in

strategy preferences, with an overall shift toward simpler, less demanding strategies. As an example, Thevenot et al. (2013) found that, to solve addition problems, older adults use retrieval strategies more frequently than calculation strategies (see also Geary et al., 1993). This shift may originate from less efficient working memory processes, as active maintenance and execution of more complex strategies are more resource demanding. Findings on age-related differences in strategy distribution will help to determine whether age-related changes in executive control are a general factor of strategic variations with age or if they influence only some strategy dimensions and not others.

Also, additional brain imaging studies could further our understanding about executive control processes involved in arithmetic strategies, and aging effects on these processes. Indeed, age-related differences in neural correlates were not documented for several experimental effects. Investigating brain activities with high temporal and/or spatial resolution techniques could provide important evidence, as this enables to find age-related differences in neural activations when no behavioral differences are found between young adults and older adults (like in strategy sequential difficulty effects; Uittenhove and Lemaire, 2013b). These neurophysiological evidence could distinguish between whether cognitive processes are preserved with age, with similar brain activations between young and older adults, or if additional, compensatory mechanisms are recruited to maintain performance similar to young adults (as observed in Hinault et al., 2016). Such findings will provide a much deeper understanding of age-related changes in processes involved during arithmetic performance.

Note that we do not mean to say that age-related changes in inhibition, working memory, and cognitive flexibility processes are the only processes to contribute to aging effects on strategic variations. Other parameters, such as processing resources and processing speed, may also have a crucial role. Indeed, Duverne et al. (2008) found that contribution of executive components in aging effects on strategic processing was attenuated when processing speed was controlled. Moreover, Duverne and Lemaire (2004) found that processing speed accounted for 70% of the variance in age-related reduction of strategy repertoire. Future research may examine how other parameters, like processing speed, may influence each strategy dimensions (ie, execution, distribution, selection) other than strategy repertoire.

At a more general level, one major research question raised by these findings is whether modulations by executive control processes can be generalized to account for aging effects in other components of numerical cognition. Indeed, age-related differences were also observed in number sense (eg, Halberda et al., 2012) and processing of symbolic numbers (eg, Wood et al., 2008). Moreover, in addition to retrieval, estimation, and computational strategies, age-related differences were also found in numerosity estimation strategies (eg, Gandini et al., 2008a,b). Future research will aim to test the hypothesis that, in addition to arithmetic performance, older adults' efficiency to represent, transcode, and quantify numbers is also modulated by efficiency of cognitive flexibility, inhibition, and working memory processes.

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