THE USE OF AUTOMATED PROCEDURES BY OLDER ADULTS WITH HIGH ARITHMETIC SKILLS DURING ADDITION PROBLEM SOLVING

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Abstract

In contrast to other cognitive abilities, arithmetic skills are known to be preserved in healthy elderly adults. In fact, they would even outperform young adults because they more often retrieve arithmetic facts from long-term memory. Nevertheless, we suggest here that the superiority of older over younger adults could also stem from the use of more efficient automated and unconscious counting procedures. We tested 35 older participants using the sign priming paradigm and selected the 18 most efficient ones, aged from 60 to 77. Sign priming are interpreted as the indicator of the pre-activation of an abstract procedure as soon as the arithmetic sign is presented. We showed that expert elderly arithmeticians behaved exactly as 26 young participants presenting the same level of arithmetic proficiency. More precisely, we showed that presenting the "+" sign 150 ms before the operands speeds up the solving process compared to a situation wherein the problem is classically presented in its whole on the screen. Only tie problems and problems involving 0 were not subjected to these priming effects and we concluded that only these problems were solved by retrieval, either of the answer for tie problems or of a rule for + 0 problems. These results could provide new insights for the conception of training programs aiming at preserving older individuals' arithmetical skills and, in a longer-term perspective, at maintaining their financial autonomy, which is decisive for keeping them in charge of their daily life.

Keywords: Numerical cognition; Successful aging; Memory network; Procedural memory; Unconscious procedures

1- INTRODUCTION

Autonomy maintenance in old age necessarily requires the preservation of numerical skills. Noticeably, mastering arithmetic constitutes the basic foundation for personal financial management through bill payment, healthcare information processing, budget planning and so on (e.g., Cahn-Weiner, Malloy, Boyle, Marran, & Salloway, 2000). It is therefore crucial to determine whether and how arithmetic skills decline with age in order to implement appropriate cognitive training to prevent or overcome deterioration (Hartley et al., 2018). If arithmetic skills do not decline with age, reinforcing these preserved capacities or basing reeducation programs upon them might be decisive in keeping the elderly in charge of their daily life.

Addition problems are initially solved through counting procedures (e.g., 3 + 2 is 3, 4, 5) by children from the age of 4 to 5 or 5 to 6 years (e.g., Dupont-Boime & Thevenot, 2018; Fuson, 1982; Siegler & Jenkins, 1989; Siegler & Shrager, 1984). After repetitive practice, procedural-based processes can be progressively replaced by more fluent memory retrieval ones (see Touron and Hertzog, 2009 for an overview) and this is exactly what is usually described in the domain of arithmetic. Counting procedures are indeed supposed to be replaced by memory retrieval of problem answers from networks stored in long-term memory (Ashcraft, 1992; 1995; Ashcraft & Battaglia, 1978; Campbell, 1995). In other words, practice would lead to the construction of arithmetic facts (e.g., 3 + 2 = 5) and problem answers could be reached without further reliance on algorithmic procedures.

It is repeatedly described in the literature that older adults rely more on retrieval of arithmetic facts from memory during arithmetic problem solving tasks than younger ones (Arnaud, Lemaire, Allen, & Michel, 2008; Geary, Frensch, & Wiley, 1993; Geary & Wiley, 1991; Thevenot, Castel, Danjon, Fanget, & Fayol, 2013). Higher or exclusive reliance on retrieval in older adults would explain how they sometimes outperform younger adults in arithmetic tasks (see Duverne and Lemaire, 2005 for a review). Still, when both young and older adults use retrieval, older adults are slower in executing the solving process (Allen et al., 2005). However, the reduced speed of execution in older adults could be due to slower operand encoding, strategy selection and verbal production of the answer rather than to the rate of retrieval per se (Allen, Ashcraft, & Weber, 1992; Allen, Smith, Jerge, & Vire-Collins, 1997; Geary & Wiley, 1991).

Nevertheless, we have recently questioned retrieval of the answers from memory as the expert strategy in mental addition by rehabilitating the disregarded conception that the development towards arithmetic proficiency consists of the acceleration of procedure execution (Baroody, 1983; 1984; 1994). We first formulated this conclusion after we showed in two experiments that, in expert young adults, problem solving is facilitated when the arithmetic sign is presented 150 ms before the operands for simple additions but not for multiplications (Fayol & Thevenot, 2012). These results were obtained using a production task and replicated previous results repeatedly obtained across three experiments using a verification task (Roussel, Barrouillet, & Fayol, 2002). The same observations were done in younger participants from the age of 12-13 years (Mathieu, Epinat-Duclos, Léone et al., 2018 in a verification task; Perez, Houiller, Mathieu, & Thevenot, unpublished manuscript in a production task). We inferred from these results that abstract procedures were primed by the "+" sign and consequently used by adults and children from the age of 12-13 years to solve addition problems. The conclusion that counting procedures are still used by adults when they solve one-digit additions was also reached through a series of experiments showing that the increase in solution times as a function of the size of problems is hard to reconcile with a retrieval-based account (Barrouillet & Thevenot, 2013; Thevenot, Barrouillet, Uittenhove, & Castel, 2016; Uittenhove, Thevenot, & Barrouillet, 2016). Brain imaging studies also reinforced our conclusions because we showed that cerebral networks devoted to spatial attention was activated when a "+" sign and not when a "×" sign was presented to young adults (Mathieu, Epinat-Duclos, Sigovan et al., 2018). We concluded that extremely fast procedures involving spatial moves on a mental number line could be used in order to solve simple additions (Mathieu, Gourjon, Couderc, Thevenot, & Prado, 2016). What is primed when the "+" sign is presented could therefore correspond to a mental representation akin to a mental number line along which individuals' attention could make displacements by one. As in Groen and Parkman's model (1972), a mental counter could be placed to a specified value corresponding to one of the two problem operands (e.g., 4 for 4 + 3) and the place of the counter could be moved by one until the number of steps represented by the other problem operand is reached (Figure 1). These procedures could be limited to four moves along a numerical sequence and automated counting procedures could therefore be limited to additions up to 4 elements (Uittenhove et al., 2016). This quantity of 4 elements corresponds to the upper limit in the subitizing range or in other words to the number of objects that individuals can capture in a glance in order to determine how many items constitute a collection (e.g., Mandler & Shebo, 1982). This limit to 4 also corresponds to the number of elements that infants and animals can compare or discriminate (Boysen & Berntson, 1989; Feigenson, Carey, & Hauser, 2002; Starkey & Cooper, 1980). In fact, this limit probably reflects the maximum number of elements that the human cognitive system can apprehend within a single attentional snapshot (Cowan, 2001). Within this limit to 4, the calculations procedures are probably run to completion by experts without awareness and this could be the reason why adults massively report retrieval for problems such as 3 + 2 or 4 + 3 (e.g., LeFevre, Sadesky, & Bisanz, 1996).

Even though retrieval model proponents have put forward several arguments against our automated counting procedure model (e.g., Campbell & Beech, 2014; Campbell & Therriault, 2013; Chen & Campbell, 2015; 2016; 2017; 2018), other teams of researchers have provided additional support for it (e.g., Baroody, 2018; De Chambrier & Zesiger, 2018;

Liu, Cai, Verguts, & Chen, 2017; Pinheiro-Chagas, Dotan, Piazza, & Dehaene, 2017; Zhu, Luo, You, & Wang, 2018; Wang, Gan, Zhang, & Wang, 2018), which attests that our model can constitute a satisfactory theoretical basis for further investigation in the domain of arithmetic.

Our conclusion that young adults use extremely fast and unconscious procedures when they solve simple additions could challenge the current conception that efficiency in arithmetic in older adults is due to higher rates of retrieval than in younger adults. Rather, it is possible that, exactly as for young adults, arithmetic problems that are usually viewed as solved through retrieval or non-retrieval strategies in older adults correspond in fact to arithmetic problems that have been processed through automated or non-automated counting procedures. In this paper, we would like to address this alternative possibility by determining whether automated counting procedures are identifiable in older adults. If it is the case, the interpretation that older adults are more efficient in mental arithmetic because they rely more on automated procedures than younger adults and not only because they use retrieval more often could be envisioned. To this aim, we used the sign priming paradigm and asked 18 older adults aged between 60 and 77 to solve addition and multiplication problems either by presenting the problems classically on their whole on the screen (i.e, null Stimulus Onset Asynchrony hereinafter referred to as SOA) or by presenting the arithmetic sign 150 ms before the operands (i.e., –150 ms SOA). This asynchrony timing of 150 ms was chosen because it had previously been showed in young adults that it corresponds to the condition in which priming effects of the sign are the neatest (Roussel, Fayol, & Barrouillet, 2002). If arithmetic problem solving mobilizes a procedural component, this procedure should be activated as soon as individuals know the nature of the task to be performed, independently of the specific problem (Anderson, 1983; Roussel, et al., 2002; Sohn & Carlson, 1998). Therefore, if presenting the arithmetic sign before the operands facilitates the solving process for additions but not for multiplications, which are known to be solved through retrieval of the answers because they are learnt by rote in school (see Jolly, 1999 for a review), then it will be possible to conclude that procedures are mobilized by older adults to solve addition problems. In fact, the only category of addition problems for which no priming effect should be observed is tie problems, universally considered as solved through retrieval (e.g., Campbell & Xue, 2001; Fayol & Thevenot, 2012; Blankenberger, 2001). In contrast, priming effects should be observed for one-digit addition problems with a sum smaller and larger than 10. Exactly as in younger adults, the size of priming effects should be similar for these two categories of problems because we have accumulated evidence showing that small problems involving very small operands are likely to be solved through automated procedures (e.g., Uittenhove et al., 2016). In fact and as explained before, automated procedures could be limited to additions up to 4 elements. Nevertheless, this does not mean that larger problems cannot involve automated procedures because their operands can be broken down into smaller ones in order to reach one or several subgoals before the final result. Moreover, we also considered problems involving 0 and 1, which are classically studied together because they are supposed to be solved by retrieval of rules rather than by retrieval of individually stored facts, namely $N + 0 = N$ and $N + 1 =$ the next number after N in the numerical sequence for additions and $N \times 0 = 0$ and $N \times 1 = N$ for multiplication (e.g., Baroody, 2004; Baroody, Eiland, Purpura, & Reid, 2012; 2013; Jost, Beinhoff, Henninghausen, & Rösler, 2004). Nonetheless and following Svenson (1985), we consider that $N + 1$ could perfectly be solved by a counting procedure and that undifferentiating the four problems might be misleading. This is the reason why we decided to study 0 and 1 problems separately. If we are right in assuming that $N + 1$ problems are processed by counting procedures as the other non-tie addition problems, then priming effects should also be observed for this problem category.

This set of results in older adults will be compared to that of a subset of younger adults collected previously for a different study (Fayol & Thevenot, 2012).

2- METHOD

2.1. Participants

Thirty-five older adults aged from 60 to 80 years (M = 69.3; SD = 5.4) took part in the experiment. All of them were in excellent physical health. Their scores on the addition and subtraction-multiplication subtests of the French Kit (French, Ekstrom, & Price, 1963, see the Material section for the detailed procedure) measuring arithmetic fluency ranged from 38 to 127 with a mean of 79 (SD = 22), which is extremely high compared to the mean score usually obtained in younger populations (53 in Thevenot et al., 2013; 59 in Thevenot, Barrouillet, Castel & Jimenez, 2011 or 64 in Thevenot, Castel, Fanget, & Fayol, 2010). The results of this population were compared to the results of 34 participants who were particularly good arithmeticians and scored between 70 and 145 on the same subsets of the French kit, with a mean of 90 (Fayol & Thevenot, 2012, Experiment 2). In order to compare the two populations, we matched the arithmetic fluency scores to a mean of 96 in the two age groups and to a minimal score of 77. This leads to 26 young adults who scored between 77 and 145 and 18 older adults (aged from 60 to 77) who scored between 77 and 127. Most older adults in this sub-sample were recruited from the University of Third Age (U3A) in Liège (N = 11), Geneva (N = 4) and Lausanne (N = 1) and two of them were family relatives to one of the experimenters in France (N =2). In order to exclude the possibility of cognitive impairment in the elderly population, the MMS (Mini Mental State) was administered (Folstein, Folstein & McHugh, 1975). Unfortunately, the MMS was not administered to the 5 participants from Switzerland. All the other participants scored more than 28, indicating normal cognition. The 26 young adults selected for this study were all psychology students at the University of Geneva and were aged between 20 to 40 with a mean age of 28 years.

The selection of high arithmetic performers in our two populations was necessary because we know that the priming effects we are seeking for cannot be observed, whatever the categories of problems, when we consider the whole population (Fayol & Thevenot, 2012). We still have to determine whether this is because subtle priming effects usually ranging from 20 to 50 ms are drowned in long solution times or whether automated procedures are not used by average or low performer individuals.

Considering that our research involved healthy individuals, it does not fall within the scope of application of the Swiss Organizational Ordinance on the Law on Research on Human Beings.

2.2. Material and procedure

2.2.1. The subtest of the French Kit

Participants completed both the addition and subtraction-multiplication subtests of the French Kit. Each subtest consists of two pages of 60 problems, for a total of four pages. Additions involve three numbers of either one or two digits (e.g., 63 + 99 + 5), subtractions involve two-digit numbers with borrows in many problems (e.g., 53 – 28), whereas multiplications consist of multiplying a two-digit by a one-digit number (e.g., 73 × 8). Subtractions and multiplications are presented in alternative rows, starting with subtractions. Therefore, half of the problems in the French kit subtest correspond to additions, one quarter to subtractions and the last quarter to multiplications. All participants were given 2 minutes per page and were instructed to solve problems as fast and as accurately as possible. The number of problems correctly solved on each of the addition and subtraction-multiplication subtest were summed to yield a total arithmetic score.

2.2.2. The arithmetic task

Participants were instructed to solve arithmetic problems by giving their answer orally as quickly and as accurately as possible. In order to construct the material, we divided the 100 possible combinations of one-digit numbers in five categories of problems. Tie problems correspond to problems with repeated operands (e.g., 3 + 3). Problems involving 1 include the operand 1 and problems involving 0 include the operand 0. Finally, large problems correspond to one-digit number problems with a sum larger than 10 (e.g., 6 9) and small problems to problems with a sum inferior or equal to 10 (e.g., 2 3). All arithmetic facts were presented in the addition and in the multiplication conditions. For both operations, the arithmetic sign was presented either 150 ms before the operands (i.e., –150 ms SOA condition) or at the same time as the operands (i.e., null SOA condition). Note that the participants who were selected from Fayol and Thevenot's sample (2012) also solved subtraction problems, for which we found significant priming effects. Moreover, participants were also confronted with an additional SOA condition wherein the operands appeared 150 ms before the arithmetic sign. This condition constituted a control in order to ensure that 150 ms preview were sufficient to reveal priming effects. It was the case and the results of this condition will not be reported here. All problems in each condition were presented twice. The total number of trials was therefore equal to 800 (i.e., 100 facts × 2 operations × 2 SOA × 2 repetitions). Because it was not possible for one participant to solve such a large set of problems, the material was divided into four sets of 200 problems and each participant was tested on one of these four sets only. The problems were randomly presented within each set.

The experiment was run under the DMDX software (Forster & Forster, 2003). Vocal responses were recorded with a voice key and individually checked off-line for accuracy using CheckVocal software (Protopapas, 2007). CheckVocal was also used to manually adjust the latencies recorded by DMDX, if necessary (e.g., when the voice key did not detect the first answer of the participant, who had then to repeat it louder). Each trial began with the presentation of a 500 ms fixation signal, followed by the presentation of the stimulus (i.e., the sign then the operands in the 150 ms SOA condition or sign and operands simultaneously in the null SOA condition) (Figure 2). The problem was displayed on the screen until a verbal response onset was detected by the voice key. Solution times corresponded to the time elapsed between the presentation of the problem in its whole and voice key activation.

3. RESULTS

The rate of correct responses in the arithmetic task was very high (mean of .97, ranging from .91 to .99 depending on the conditions). A 2 (Operation: addition vs. multiplication) × 2 (SOA: –150 ms vs. null) × 5 (Type of Problems: tie, large, small, involving 0 or involving 1) × 2 (Age: Younger vs. Older adults) repeated measures ANOVA with the last variable as a between measure was performed on mean solution times revealed a main effect of Operation (.99 vs. .96 for addition and multiplication respectively, $F(1, 34) = 12.90$, $MSE = .01$, $\eta_p^2 = .28$, $p = .001$). The effect of Type of Problems was also significant, $F(4, 136) = 8.56$, $MSE = .01$, $\eta_p^2 = .20$, $p < .001$). The highest rates of correct responses were associated with small, tie and n + 1 problems (.99 for the 3 categories of problems), followed by n + 0 problems (.97). Large problems were associated with the lowest rate of correct responses (.95). Finally there was an interaction between Operation and Type of Problems, $F(4, 136) = 5.52$, $MSE = .01$, $\eta_p^2 = .14$, $p < .001$ showing that the difference between large problems and the other types of problems was due to multiplication (.92 vs.98) rather than addition (.98 vs .99). No other effect reached significant. Noticeably, the effect of Age was not significant and did not interact with any of the variables.

The analysis on solution times was carried out on correctly solved problems only (i.e., 89.6% of the trials). Technical recording errors and outliers (below 200 ms and more than 2 standard deviations away from the participants' mean) were also discarded from the analysis (i.e., 3.7% of the data). A 2 (Operation: addition vs. multiplication) × 2 (SOA: –150 ms vs. null) × 5 (Type of Problems: tie, large, small, involving 0 or involving 1) × 2 (Age: Younger vs. Older adults) repeated measures ANOVA with the last variable as a between measure was performed on mean solution times (Table 1). There was an effect of Age, $F(1, 42) = 8.99$, $MSE = 2202948.56$, $\eta_p^2 = .18$, $p < .01$, showing that older adults were slower (872 ms) than younger ones (771 ms) but there was no effect of Operation, (815 ms for addition and 828 ms for multiplication), $F(1, 42) = 2.36$, $MSE = 32933.09$, $p = .13$ or interaction between Operation and Age, $F(1, 42) = 1.57$, $MSE = 21908.71$, $p = .22$. However, solution times varied as a function of Type of problems, $F(4, 168) = 58.38$, $MSE = 1027741.17$, $\eta_p^2 = .58$, $p < .001$. Large problems were solved slower (947 ms) than problems involving 0 (835 ms, $F(1, 42) = 32.71$, $\eta_p^2 = .44$, $p < .001$), which were not solved slower than small problems (809 ms, $F(1, 42) = 2.14$, $p = .15$). Small problems were solved slower than tie problems (770 ms, $F(1, 42) = 12.60$, $\eta_p^2 = .23$, $p < .01$), and tie problems were solved slower than problems involving 1 (747 ms, $F(1, 42) = 7.17$, $\eta_p^2 = .15$, $p = .01$). The effect of Type of problems interacted with Age ($F(4, 168) = 15.13$, $MSE = 266439.33$, $\eta_p^2 = .27$, $p < .001$) showing that whereas problems involving 1 were solved the fastest and large problems the slowest by both age groups, the order of problem types according to their solution times differs within each age group (see Table 1). Nevertheless, the effect of Type of problems was significant for both age groups ($F(4, 39) = 36.98$, $\eta_p^2 = .79$, $p < .001$ for younger adults and $F(4, 39) = 19.25$, $\eta_p^2 = .66$, $p < .001$ for older adults). There was also a main effect of SOA, $F(1, 42) = 21.74$, $MSE = 90542.79$, $\eta_p^2 = .34$, $p < .001$. Problems were solved faster when the sign appeared before the operands (811 ms) than when it appeared at the same time (832 ms). The SOA effect did not interact with Age ($F(1, 42) = 1.29$, $MSE = 5353.93$, $p = .26$) showing that in both age groups problems with negative SOA were solved faster than those with null SOA

($F(1, 42) = 7.61$, $\eta_p^2 = .15$, $p < .01$ for younger adults and $F(1, 42) = 14.21$, $\eta_p^2 = .25$, $p < .01$ for older adults).

More interestingly, the interaction between Operation and SOA was significant, $F(1, 42) = 8.21$, $MSE = 24260.40$, $\eta_p^2 = .16$, $p < .01$, showing that the facilitation effect when the sign was presented before the operands was larger for addition (31 ms), $F(1, 42) = 33.00$, $\eta_p^2 = .44$, $p < .001$, than for multiplication (10 ms), $F(1, 42) = 2.66$, $p = .11$. This interaction did not interact further with Age ($F(1, 42) < 1$, $MSE = 10.89$). The effect of SOA was larger for addition than multiplication in both populations (27 vs. 5 ms in young adults and 36 vs. 15 ms in older adults, for addition vs. multiplication respectively).

There was no significant Operation × Type × SOA ($F(4, 168) = 1.18$, $MSE = 3371.70$, $p = .32$) nor Operation × Type × SOA × Age ($F(4, 168) < 1$, $MSE = 1151.65$) interactions. This last result was confirmed by a Bayesian repeated-measures ANOVA comparing models with and without the 4-variable interaction. The result strongly favored the model without interaction, $\underline{BF}_{01} = 19.71$. However, because we formulated specific predictions regarding SOA effects as a function of the nature of problems, we carried out a series of planned comparisons in each of the population. For addition in older adults, presenting the sign before the operands was facilitating for large problems (43 ms, $F(1, 42) = 5.44$, $\eta_p^2 = .11$, $p = .02$), small problems (55 ms, $F(1, 42) = 7.11$, $\eta_p^2 = .15$, $p = .01$) and problems involving 1 (34 ms, $F(1, 42) = 17.19$, $\eta_p^2 = .29$, $p < .001$), but not for tie problems (24 ms, $F(1, 42) = 1.04$, $p = .31$) nor for problems involving 0 (25 ms, $F(1, 42) < 1$). The same pattern was observed for younger adults, with a facilitating effect of 29 ms for large problems ($F(1, 42) = 7.62$, $\eta_p^2 = .15$, $p < .01$), of 31 ms for small problems ($F(1, 42) = 15.32$, $\eta_p^2 = .27$, $p < .001$), of 55 ms for problems involving 1($F(1, 42) = 4.57$, $\eta_p^2 = .10$, $p = .04$) but a non-significant effect of 20 ms for tie problems ($F(1, 42) = 1.12$, $p = .30$) and of –3 ms for problems involving 0 ($F(1, 42) = 1.74$, $p = .20$). For multiplication in young and older adults, there was no type of problems for which presenting the sign before the operands was significantly facilitating (20 ms for large problems, $F < 1$; 31 ms for small problems, $F(1, 42) = 1.64$, $p = .21$; –9 ms for problems involving 1, $F < 1$; 33 ms for tie problems, $F < 1$; and 1 ms for problems involving 0, $F < 1$ in older adults and –6 ms for large problems, $F(1, 42) = 1.30$, $p = .26$; 19 ms for small problems, $F(1, 42) = 2.96$, $p = .09$; 3 ms for problems involving 1, $F < 1$; 5 ms for tie problems, $F(1, 42) = 3.29$, $p = .08$; and 3 ms for problems involving 0, $F < 1$ in younger adults) (see Table 1).

For the contrasts where a significant SOA effect was found, we conducted a Bayesian paired sample *t*-test with a Cauchy prior scale of 0.707. In younger adults, the estimated inverse Bayes factor (alternative/null) for small and large addition problems suggested an anecdotal support ($BF_{10} = 2.68$ and 2.30 for small and large problems, respectively) for alternative hypothesis of a model including a SOA effect. Nevertheless, even if anedoctal, the support is always in favor of the alternative hypothesis irrespective of the prior. Moreover, the support for alternative hypothesis was decisive ($BF_{10} = 699.28$) for problems involving 1. In older adults, the support for alternative hypothesis was substantial for large addition problems ($BF_{10} = 3.41$) and very strong for small addition problems ($BF_{10} = 86.12$). However, contrary to the frequentist approach repported above, the estimated Bayes factor (null/hypothesis) of $BF_{01} = 1.81$ for 1-digit addition problems suggested an anecdotal support for null hypothesis of a model without an effect of SOA.

3. **DISCUSSION**

This study was conducted in order to determine whether automated counting procedures can be revealed in older adults with high arithmetic skills when they solve simple addition problems. As already mentioned in the Introduction, older individuals are supposed to often resort to memory retrieval when they solve simple arithmetic problems (Duverne &

Lemaire, 2005; Geary & Wiley, 1991; Thevenot et al., 2013). Nevertheless, we have recently advocated that procedural strategies can sometimes be mistaken for retrieval in young adults (Barrouillet & Thevenot, 2013; Fayol & Thevenot, 2012; Uittenhove et al., 2016) and it is important for theoretical and practical reasons to establish whether it is also the case in older individuals. First, in view of the scores obtained by our participants on an arithmetic fluency test, we replicated the results that healthy older adults present higher arithmetic abilities than younger individuals (see Duverne and Lemaire, 2005 for a review). More importantly here, when we selected a sub-population of 18 older adults who were even more efficient than the general population, we showed that solution times were speeded up when the "+" sign is presented 150 ms before the operands. This replicated what was previously observed in efficient young adults (Fayol & Thevenot, 2012; Mathieu et al., 2018; Roussel et al., 2002). As already explained in the Introduction, this facilitation is interpreted as an indication that a procedure is pre-activated and subsequently used to solve the problem (Sohn & Carlson, 1998). Again as in younger adults, this effect was not observed when the "×" sign was presented before the operands. This different pattern of results for addition and multiplication supports the interpretation that it is a procedure that is pre-activated and used to solve addition problems as soon as the "+" sign is read on the screen whereas a procedure is not pre-activated for multiplication problems. Note that the lack of priming effect for multiplication does not mean that all problems are solved by retrieval of the answer from memory (Prado et al., 2013) but that a ready-made and abstract procedure that could be applied to solve multiplication problems is not pre-activated by the "×" sign.

An alternative interpretation of our results is that presenting the sign before the operands pre-activates a network of memorized arithmetic facts rather than an abstract procedure. However, in that case, priming effects should also have been observed for multiplication, which, due to the rote memorization of multiplication table in school, is unanimously viewed as solved through memory retrieval of the answers in a mental network (e.g., De Visscher, Berens, Keidel, Noel, & Bird, 2015; De Visscher & Noel, 2014; De Visscher et al., 2018; Ischebeck et al., 2006; Stazyck, Ashcraft, & Hamman, 1982). Still, it would be possible that the addition network is more easily activated than the multiplication network. However, in this context, it would be difficult to explain why addition tie problem solving would not be facilitated by prior presentation of the "+" sign. A last argument that can be formulated against the interpretation that the arithmetic signs pre-activates semantic networks of arithmetic operations is that priming effects are observable when a "-" sign is presented before a subtraction (Roussel et al., 2002; Fayol & Thevenot, 2012). Subtraction is viewed by researchers in the domain of numerical cognition as mainly solved by calculation procedures and are therefore not viewed as represented in a semantic network (Campbell & Xue, 2001; Dehaene, 1992; Robinson, 2001; Seyler, Kirk & Ashcraft, 2003; Thevenot & Barrouillet, 2006). Therefore, facilitation effects due to the presentation of an arithmetic sign before the operands cannot be interpreted only in terms of activation of a semantic network.

The general pattern of results reported here, namely priming effect of the "+" sign for addition but no sign priming for multiplication, was modulated by the types of problems under study. For tie addition problems, no priming effect of the "+" sign was observed, which reinforces previous conclusions of the literature that these problems have a special status and are mainly solved through a retrieval strategy (e.g., Bagnoud, Dewi, Castel, Mathieu, & Thevenot, under review; Campbell & Gunter, 2002). Highly interestingly, whereas special additions involving 0 and 1 are often considered together and viewed as solved through the use of rules and heuristics (e.g., Ashcraft, 1992; Baroody et al., 2012; 2013; Baroody, Purpura, Eiland & Reid, 2015), a differential pattern of priming was obtained for these two categories of problems. For both young and older adults, we observed a priming effect for + 1 problems but not for + 0 problems. Therefore, whereas + 0 problems seem to be solved by the retrieval of a rule, + 1 problems seem to be processed by the same kind of abstract procedure as the other simple non-tie arithmetic problems. It has been repeatedly suggested that the procedure that is primed by the “+” sign could consist in the activation of the mental number line and the preparation to scroll it from left to right (Fayol & Thevenot, 2012; Li et al., 2018; Liu et al., 2017; Mathieu et al., 2016; Pinheiro-Chagas et al., 2017; Zhu et al., 2018). The results that we obtain suggest that both young and older adults solve + 1 problems by performing one step to the left of the other addend on the mental number line. This corresponds to a standard counting procedure and not to the application of a rule. This result is important because it questions the methodology and the interpretation of previous studies considering + 0 and + 1 problems as a unitary category of problems concerning the strategies used for their resolution (e.g., Campbell & Xue, 2001; Fayol & Thevenot, 2012). Interestingly, such a dissociation between 0 and 1 problems has already be documented in the domain of multiplication by Allen et al. (2005) who showed that older adults make more errors than younger ones for x 0 problems but not for x 1 problems. The authors concluded that rule retrieval was impaired in older adults and therefore suggested that x 1 problems were processed exactly as other multiplication involving operands different from 0. Nevertheless, concerning our results, it has to be noted that whereas Bayesian statistics strongly support priming effect for + 1 problems in younger adults and therefore the use of procedure for this category of problem in this population, the evidence was weaker in older adults. Future experiments will therefore need to replicate those results in older adults before firmer conclusions can be drawn concerning the use of automated procedures for + 1 problems.

Thus, this study is the first suggesting that the advantage of elderly adults in arithmetic tests might not entirely be related to their better memorization of arithmetic facts compared to younger individuals. Exactly as younger expert adults, older adults present behaviors that are interpreted as reflecting the use of automated counting procedures. If we extrapolate our results to the general population, it is therefore possible that the superiority of older adults in the domain of mental arithmetic might, at least in part, stem from a more systematic use of automated and unconscious counting procedures. This would be coherent with the fact that, whereas acquisition of new procedural skills is more difficult in older than younger adults (e.g., Charness & Campbell, 1988), "there is a consensus that older adults have lasting preservation of procedural or motor memory" (Brickman & Stern, 2009, p.177). In support to our conclusions, it is striking to observe in our results that the categories of problems that we interpret as being processed through automated procedures because they benefit from the prior presentation of the "+" sign are solved only 52 ms slower by older than younger adults in the null SOA condition (i.e., difference of only 34, 64 and 59 ms for Large, Small and +1 additions respectively) when older adults suffer more than triple the times (+162 ms) for addition problems that we interpret as being solved by retrieval (i.e., +215 ms and +110 for +0 and tie problems, respectively). Again, this is perfectly coherent with the view that older adults present only slight procedural access and execution impairments, especially when the procedure has been intensively practiced through lifetime (Krampe & Ericsson, 1996) but significantly slower semantic access speed than younger ones (Petros, Zehr, & Chabot, 1983).

Before concluding, we would like to insist on the fact that our results have been collected in older adults who have particularly well preserved and particularly high arithmetic skills. This sub-sample of participants corresponded to slightly more than half of our original sample. Nevertheless, the characteristics of our paradigm do not allow the generalization of our interpretations to the whole population of elderly individuals. We encounter exactly the same limitations when younger adults are under study (Fayol & Thevenot, 2012), maybe because subtle priming effects (i.e., maximum of 55 ms in the present experiment) are easily drowned in long solution times. Therefore and up to now, we do not know whether this lack of priming effects in the more general population means that automated procedures are not used by less efficient individuals or whether our paradigm fails to reveal them. Future experiments using technics that investigate brain functioning might advance our understanding concerning this topic and might allow us to generalize our results to the whole population. Still, our results that at least some older adults could use automated counting procedures can shed light or modulate previous results and conclusions of the literature in the more general population of older adults. Indeed, the superiority in arithmetic of older over younger adults is necessarily partly due to some extremely efficient seniors. We show here that the high efficiency of these participants can be due to the use of automated counting procedures and we therefore contribute to provide an explanation for the particularly good arithmetic skills of older adults in the general population.

More generally, the present experiment conducted in older adults allows us to replicate the results we obtained in younger individuals and therefore to strengthen the reliability of our conclusions related to automated counting procedures for addition. Revealing that the results of simple non-tie additions could still be computed using procedural strategies in expert adults is crucial both on theoretical and more practical levels. First, our results question one of the main tenets of the associationist theory, according to which elements that are represented in close contiguity in a mental space are necessarily associated and necessarily retrieved as an association from long-term memory (Thorndike, 1911). Our results strongly suggest that one of the most repetitive cognitive activities, namely mental addition, does not necessarily result in the construction of associations between operands and answers but rather in the automatization of counting procedures. Therefore, an alternative model to the dominant one (e.g., Logan, 1988; Logan & Klapp, 1991) might need to be formulated in order to account for the automatization of learning (Thevenot, Dewi, Bagnoud, Uittenhove, & Castel, under review). On a more applied point of view, providing evidence that arithmetic expertise in addition is most likely to be achieved through procedural automatization than retrieval of the answers from long-term memory suggests that overemphasize of rote memorization during learning may be misguided. Instead, repeated use of a procedure as counting might be more efficient than memorization of direct associations between operands and answers.

To conclude and more in relation with cognitive aging, the results of the present study suggest that preserved and efficient procedural arithmetic skills can be observed in older adults with high arithmetic skills. These automated counting procedures can therefore be considered as a good mental tool and a strong strength for maintenance of financial and thus daily life autonomy. As a consequence, it might be valuable to train these counting procedures through intensive practice in adults who do not age so successfully. Unfortunately, it is known that intensive practice in old age does not bring the same level of performance than the one reached by younger adults (Maquestiaux, Didierjean, Ruthruff, Chauvel, & Hartley, 2013; Touron, Hoyer, & Cerella, 2001). Consequently and in order to ensure automatization of arithmetic procedures, we think that it is necessary that training programs take place before the cognitive system departs excessively from its optimum level of efficiency. More generally, our results suggest that training program in arithmetic might need to be conceived and administered to adults of the new generations, who did not experience such intensive practice in school compared to individuals belonging to the older generations. In the United States, a cross-generational decline in arithmetical competencies has indeed been well documented by Schaie (1996) who indicates a drop in arithmetic performance for individuals who received their primary education after the mid-60's compared to individuals who received their education just before or just after the Second World War. According to Geary and Lin (1998), this cross-generational decline could explain why older adults sometimes outperform younger ones (Geary, Salthouse, Chen, & Fan, 1996; Geary et al., 1997). The main explanations provided by Geary et al. (1996) for the decline in arithmetic performance over generations is a decrease in the teaching of problem decompositions as a strategy to solve addition and subtraction problems (e.g., 7 + 8 = 7 + 7 +1). According to the authors, this type of strategy could promote retrieval of arithmetic facts. Nevertheless, as advocated in the present paper, the advantage of older adults over younger ones could also stem from a better automatization of counting procedures rather than only from higher reliance on retrieval of arithmetic facts. Therefore, our results suggest that more intensive practice of counting procedures in primary schools could also constitute a useful tool to help future young and older adults to strengthen and preserve their arithmetic abilities. It turns out that it has already been demonstrated that an intervention based on repetitive counting-on from the largest addend of an addition problem (3 + 4 = 5, 6, 7) is more efficient to develop arithmetic skills than a training program based on drill and practice (Tournaki, 2003). However, our results do not exclude the fact that older adults sometimes outperform younger ones because of more frequent reliance on retrieval. For example, more intensive practice of arithmetic in schools in the past probably led to better consolidation of multiplication facts in older generations than in younger ones. Nevertheless, the present research highlights the possibility that, in addition to a retrieval fact advantage, healthy older adults use automated procedures better an more often than their younger counterparts.

Finally, beyond arithmetic, our study addresses the general question of the role of strategies in cognitive aging (Lemaire, 2016). It has been shown that despite general cognitive decline with age, older adults can maintain a high level of performance in certain domains either by keeping stable and well-oiled strategies or by changing and adapting previous strategies. Our conclusions definitely fall within the first possibility and nourish the idea that expertise can annihilate cognitive decline due to aging. For example, Salthouse (1984) showed that typing speed decreases with age only in participants with a low level of typing expertise. The interpretation of this result is that, through automatization, the cognitive load of the task is reduced. As well established by Lemaire (2016), it turns out that the domains that are less subjected to deleterious aging effects are the least demanding in terms of cognitive resources. Therefore, our research supports the view that intensive repetition of procedural knowledge throughout the entire life is one of the keys for successful aging.

References

Allen, P. A., Ashcraft, M. H., & Weber, T. A. (1992). On mental multiplication and age. *Psychology and Aging, 7*, 536-545.

Allen, P .A ., Bucur, B ., Lemaire, P ., Duverne, S ., Ogrocki, P ., & Sanders, R .E . (2005). Influence of probable Alzheimer's disease on multiplication verification and production. *Aging, Neuropsychology, and Cognition*, *12*, 1-31.

Allen, P. A., Smith, A. F., Jerge, K. A., & Vires-Collins, H. (1997). Age differences in mental multiplication: Evidence for peripheral but not central decrements. *Journal of Gerontology: Psychological Sciences, 52b*, 81-90.

Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.

Arnaud, L., Lemaire, P., Allen, P., & Michel, B. F. (2008). Strategic aspects of young, healthy older adults', and Alzheimer patients' arithmetic performance. *Cortex, 44*, 119-130.

Ashcraft, M. H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition, 44,* 75-106.

Ashcraft, M. H. (1995). Cognitive psychology and simple arithmetic: A review and summary of new directions. *Mathematical Cognition*, *1*, 3-34.

Ashcraft, M.H., & Battaglia, J. (1978). Cognitive arithmetic: Evidence for retrieval and decision processes in mental addition. *Journal of Experimental Psychology: Human Learning and Memory, 4*, 527-538.

Bagnoud, J., Dewi, J., Castel, C., Mathieu, R., & Thevenot, C. (under review). Developmental changes in size effects for addition problems in 6- to 12 year-old-children and adults.

Baroody, A.J. (1983). The development of procedural knowledge: An alternative explanation for chronometric trends of mental arithmetic. *Developmental Review, 3*, 225-230.

Baroody, A.J. (1984). A reexamination of mental arithmetic models and data: A reply to Ashcraft. *Developmental Review, 4*, 148-156.

Baroody, A.J. (1994). An evaluation of evidence supporting fact-retrieval models. *Learning and Individual Differences, 6*, 1-36.

Baroody, A. J. (2004). The developmental bases for early childhood number and operations standards. In D. H. Clements, J. Sarama, & A.-M. DiBiase (Eds.), *Engaging young children in mathematics: Standards for early childhood mathematics education* (pp. 173-219). Mahwah, NJ: Lawrence Erlbaum.

Baroody, A. J. (2018). A commentary on Chen and Campbell (2017): Is there a clear case for addition fact recall? *Psychonomic Bulletin & Review*, *25*, 2398-2405.

Baroody, A. J., Eiland, M. D., Purpura, D. J., & Reid, E. E. (2012). Fostering at-risk kindergarten children's number sense. *Cognition and Instruction, 30,* 435-470.

Baroody, A. J., Eiland, M. D., Purpura, D. J., & Reid, E. E. (2013). Can computer-assisted discovery learning foster first graders' fluency with the most basic addition combinations? *American Educational Research Journal, 50,* 533-573.

Baroody, A. J., Purpura, D. J., Eiland, M. D., & Reid, E. E. (2015). The impact of highly and minimally guided discovery instruction on promoting the learning of reasoning strategies for basic add-1 and doubles combinations. *Early Childhood Research Quarterly, 30,* 93-105.

Barrouillet, P., & Thevenot, C. (2013). On the problem size effect in small additions: Can we really discard any counting-based account? *Cognition, 128,* 35-44.

Blankenberger, S. (2001). The arithmetic tie effect is mainly encoding-based. *Cognition*, *82*, B15-B24.

Boysen, S. T., & Berntson, G. G. (1989). Numerical competence in a chimpanzee (Pan troglodytes). *Journal of Comparative Psychology, 103*, 23–31.

Brickman, A. M., & Stern, Y. (2009). Aging and memory in humans. *Encyclopedia of Neuroscience, 1,* 175-180.

Cahn-Weiner, D. A., Malloy, P. F., Boyle, P. A., Marran, M., & Salloway, S. (2000). Prediction of functional status from neuropsychological tests in community-dwelling elderly individuals. *The Clinical Neuropsychologist*, *14*, 187-195.

Campbell, J. I. D. (1995). Mechanisms of single addition and multiplication: A modified network-interference theory and simulation. *Mathematical Cognition, 1*, 121-164.

Campbell, J. I. D., & Beech, L. C. (2014). No generalization of practice for nonzero simple addition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1766-1771.

Campbell, J. I. D., & Gunter, R. (2002). Calculation, culture and the repeated operand effect. *Cognition, 86*, 71-96.

Campbell, J. I. D., & Therriault, N. H. (2013). Retrieval-induced forgetting of arithmetic facts but not rules. *Journal of Cognitive Psychology*, *25*, 717-724.

Campbell, J. I. D., & Xue, Q. (2001). Cognitive arithmetic across cultures. *Journal of Experimental Psychology: General, 130*, 299-315.

Charness, N., & Campbell, J. I. D. (1988). Acquiring skill at mental calculation in adulthood: A task decomposition. *Journal of Experimental Psychology: General, 117*(2), 115-129.

Chen, Y., & Campbell, J. I. D. (2015). Operator and operand preview effects in simple addition and multiplication: A comparison of Canadian and Chinese adults. *Journal of Cognitive Psychology*, *27*, 326-334.

Chen, Y., & Campbell, J. I. D. (2016). Operator priming and generalization of practice in adults' simple arithmetic. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*, 627-635.

Chen, Y., & Campbell, J. I. D. (2017). Transfer of training in simple addition. *The Quarterly Journal of Experimental Psychology*, *71*, 1312-1323.

Chen, Y., & Campbell, J. I. D. (2018). "Compacted" procedures for adults' simple addition: A review and critique of the evidence. *Psychonomics Bulletin & Review*, *25*, 739-753.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24,* 87-185.

de Chambrier, A.-F., & Zesiger, P. (2018). Is a fact retrieval deficit the main characteristic of children with mathematical learning disabilities? *Acta Psychologica*, *190*, 95-102.

Dupont-Boime, J., & Thevenot, C. (2018). High working memory capacity favours the use of finger counting in six-year-old children. *Journal of Cognitive Psychology*, *30*, 35-42.

Duverne, S., & Lemaire, P. (2005). Aging and Arithmetic. In J. I. D. Campbell (Ed.), *The Handbook of Mathematical Cognition* (pp. 397-411). London: Psychology Press.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1-42.

De Visscher, A., Berens, S. C., Keidel, J. L., Noël, M.-P., & Bird, C. M. (2015). The interference effect in arithmetic fact solving: An fMRI study. *Neuroimage, 116,* 92-101.

De Visscher, A., & Noël, M.-P. (2014). Arithmetic facts storage deficit: the hypersensitiviy-to-interference in memory hypothesis. *Developmental Science*, *17*, 434-442.

De Visscher, A., Vogel, S.E., Reishofer, G., Hassler, E., Koschuntig, K., De Smedt, B., & Grabner, R. H. (2018). Interference and problem size effect in multiplication fact solving:Individual differences in brain activations and arithmetic performance. *Neuroimage, 172*, 718-727.

Fayol, M., & Thevenot, C. (2012). The use of procedural knowledge in simple addition and subtraction problems. *Cognition, 123,* 392-403.

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files vs. analog magnitudes. *Psychological Science, 13*, 150-156.

Folstein, M.F., Folstein, S.E., McHugh, P.R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 2*,189-198.

Forster, K. I., & Forster, J. C. (2003). DMDX: A window display program with millisecond accuracy. *Behavior, Research Methods, Instruments and Computers, 35,* 116-124.

French, J. W., Ekstrom, R. B., & Price, I. A. (1963). *Kit of reference tests for cognitive factors*. Princeton, NJ: Educational Testing S.

Fuson, K. C. (1982). An analysis on the counting on solution procedure in addition. In T. P. Carpenter, J. M. Moser, & T. A. Romberg (Eds.), *Addition and subtraction: A cognitive perspective* (pp. 67-81). Hillsdale NJ: Lauwrence Erlbaum.

Geary, D. C., Frensch, P. A., & Wiley, J. G. (1993). Simple and complex mental subtraction: Strategy choice and speed-of-processing differences in young and elderly adults. *Psychology and Aging, 8*, 242-256.

Geary, D. C., Hamson, C. O., Chen, G. P., Liu, F., Hoard, M. K., & Salthouse, T. A. (1997). Computational and reasoning abilities in arithmetic: Cross-generational change in China and the United States. *Psychonomic Bulletin & Review, 4*, 425-430.

Geary, D. C., & Lin, J. (1998). Numerical cognition: Age-related differences in the speed of executing biologically-primary and biologically-secondary processes. *Experimental Aging Research, 24*, 101-137.

Geary, D. C., Salthouse, D. C., Chen, G. P., & Fan, L. (1996). Are East Asian versus American differences in arithmetical ability a recent phenomenon? *Developmental Psychology, 32*, 254-262.

Geary, D.C., & Wiley, J.G. (1991). Cognitive addition: Strategy choice and speed of processing differences in young and elderly adults. *Psychology and Aging, 6*, 474-483.

Groen, G. J., & Parkman, J. M. (1972). A chronometric analysis of simple addition. *Psychological Review, 79*, 329-343.

Hartley, A., Hartley, J., Didierjean, A, Maquestiaux, F., Angel, L., Castel, A., Geraci, L., Hazeltine, E., Lemaire, P., Ruthruff, E., Taconnat, L., Thevenot, C., & Touron, D. (2018). Successful aging: The role of cognitive gerontology. *Experimental Aging Research, 44,* 82-93.

Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstatter, F., Benke, T., Felber, S., Delazer, M. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. *Neuroimage, 30*, 1365-1375.

Jolly, M. D. (1999). *Automatic Recall of Multiplication Facts and Number Sense* (Doctoral Thesis). Retrieved from https://ro.ecu.edu.au/theses_hons/836.

Jost, K., Beinhoff, U., Hennighausen, E., & Rösler, F. (2004). Facts, rules, and strategies in single-digit multiplication: evidence from event-related brain potentials. *Cognitive Brain Research*, *20*, 183-193.

Krampe, R. T., & Ericsson, K. A. (1996). Maintaining excellence: Deliberate practice and elite performance in young and older pianists. *Journal of Experimental Psychology: General, 125*, 331-359.

LeFevre, J.-A., Sadesky, G. S., & Bisanz, J. (1996). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory and Cognition, 22*, 216-230.

Lemaire, P. (2016). *Cognitive aging: The role of strategies*. New York, NY, US: Routledge/Taylor & Francis Group.

Li, M., Liu, D., Li, M., Dong, W., Huang, Y., & Chen, Q. (2018). Addition and subtraction but not multiplication and division cause shifts of spatial attention. *Frontiers in Human Neuroscience, 12*, 183.

Liu, D., Cai, D., Verguts, T., & Chen, Q. (2017). The time course of spatial attention shifts in elementary arithmetic. *Scientific Reports*, *7*, 921.

Logan, G.D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492-527.

Logan, G. D., & Klapp, S. T. (1991). Automatizing alphabet arithmetic: I. Is extended practice necessary produce automaticity? *Journal of Experimental Psychology: Learning, Memory and Cognition, 17*, 179-195.

Maquestiaux, F., Didierjean, A., Ruthruff, E., Chauvel, G., & Hartley, A. (2013). Lost ability to automatize task performance in old age. *Psychonomic Bulletin & Review, 20,* 1206-1212.

Mandler, G., & Shebo, B. J. (1982). Subitizing: an analysis of its component processes. *Journal of Experimental Psychology, 111,* 1-22.

Mathieu, R., Gourjon, A., Couderc, A., Thevenot, C., & Prado, J. (2016). Running the number line: Rapid shifts of attention in single-digit arithmetic. *Cognition*, *146*, 229-239.

Mathieu, R., Epinat-Duclos, J., Léone, J., Fayol, M., Thevenot, C., & Prado, J. (2018). Hippocampal spatial mechanisms scaffold the development of arithmetic symbol processing in children. *Developmental Cognitive Neuroscience*, *30*, 324-332.

Mathieu, R., Epinat-Duclos, J., Sigovan, M., Breton, A., Cheylus, A, Fayol, M., Thevenot, C., & Prado, J. (2018). What's behind a "+" sign? Perceiving an arithmetic operator recruits brain circuits for spatial orienting. *Cerebral Cortex*, *28*, 1673-1684.

Perez, J-F, Houillon, J- C., Mathieu, R., Prado, J., & Thevenot, C. (unpublished manuscript). Priming effects of the arithmetic sign in 10- to 15-year-old children.

Petros, T. V., Zehr, H. D., & Chabot, R. J. (1983). Adult age differences in accessing and retrieving information from long-term memory. *Journal of Gerontology*, *38*, 589-592.

Pinheiro-Chagas, P., Dotan, D., Piazza, M., & Dehaene, S. (2017). Finger tracking reveals the covert stages of mental arithmetic. *Open Mind*, *1*, 30-41.

Prado, J., Lu, J., Liu, L., Dong, Q., Zhou, X., & Booth, J. R. (2013). The neural bases of the multiplication problem-size effect across countries. *Frontiers in Human Neuroscience*, *7*, 189.

Protopapas, A. (2007). CheckVocal: A program to facilitate checking the accuracy and response time of vocal responses from DMDX. *Behavior Research Methods, 39*, 859-862.

Robinson, K. M. (2001). The validity of verbal reports in children's subtraction. *Journal of Educational Psychology, 93*, 211-222.

Roussel, J.L., Fayol, M., & Barrouillet, P. (2002). Procedural vs. direct retrieval strategies in arithmetic: A comparison between additive and multiplicative problem solving. *European Journal of Cognitive Psychology, 14,* 61-104.

Salthouse, T. A. (1984). Effects of age and skill on typing. *Journal of Experimental Psychology : General, 13*, 345-371.

Schaie, K. W. (1996). *Intellectual development in adulthood: The Seattle Longitudinal Study.* New York: Cambridge University Press.

Seyler, D. J., Kirk, E. P., & Ashcraft, M. H. (2003). Elementary subtraction. *Journal of Experimental Psychology: Learning, Memory and Cognition, 29*, 1339-1352.

Siegler, R. S., & Jenkins, E. (1989). *How children discover new strategies*. Hillsdale, NJ: Erlbaum.

Siegler, R. S., & Shrager, J. (1984). Strategic choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 229-293). Hillsdale: Erlbaum.

Sohn, M.-H, & Carlson, R. A. (1998). Procedural frameworks for simple arithmetic skills. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*, 1052-1067.

Starkey, P., & Cooper, R. G., Jr (1980). Perception of numbers by human infants. *Science*, *210*, 1033-1035.

Stazyk, E. H., Ashcraft, M. H., & Hamann, M. S. (1982). A network approach to mental multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *8*, 320–335.

Svenson, O. (1985). Memory retrieval of answers of simple additions as reflected in response latencies. *Acta Psychologica*, *59*, 285-304.

Thevenot, C., & Barrouillet, P. (2006). Encoding numbers: Behavioral evidence for processing-specific representations. *Memory & Cognition, 34,* 938-948.

Thevenot, C., Barrouillet, P., Uittenhove, K., & Castel, C. (2016). Ten-year-old children strategies in mental addition: A counting model account. *Cognition*, *146*, 48-57.

Thevenot, C., Barrouillet, P., Castel, C., & Jimenez, S. (2011). Better elementary number processing in higher skilled arithmetic problem solvers: Evidence from the encoding step. *Quarterly Journal of Experimental Psychology, 64,* 2110-2124.

Thevenot, C., Castel, C., Danjon, J., Fanget, M., & Fayol, M. (2013). The use of the operand-recognition paradigm for the study of mental addition in older adults. *Journal of Gerontology: Psychological Sciences, 68,* 64-67.

Thevenot, C., Castel, C., Fanget, M., & Fayol, M. (2010). Mental subtraction in high and lower-skilled arithmetic problem solvers: Verbal report vs. operand-recognition paradigms. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *36*, 1242-1255.

Thevenot, C., Dewi, J., Bagnoud, J., Uittenhove, K., & Castel, C. (under review). Evidence for retrieval in alphabet arithmetic tasks is biased by end-term effects.

Thorndike, E. (1911). *Animal intelligence: Experimental studies*. New York: Macmillan.

Tournaki, N. (2003). The differential effects of teaching addition through strategy instruction versus drill and practice to students with and without learning disabilities. *Journal of Learning Disabilities, 36*, 449-458.

Touron, D. R., & Hertzog, C. (2009). Age differences in strategic behaviour during a computation-based skill acquisition task. *Psychology and Aging, 24,* 574-585.

Touron, D. R., Hoyer, W. J., & Cerella, J. (2001). Cognitive skill acquisition and transfer in younger and older adults. *Psychology and Aging, 16,* 555-563.

Uittenhove, K., Thevenot, C., & Barrouillet, P. (2016). Fast automated counting procedures in addition problem solving: When are they used and why are they mistaken for retrieval? *Cognition*, *146*, 289-303.

Wang, L. H., Gan, J. Q., Zhang. L., & Wang, H. X. (2018). Differential recruitment of brain networks in single-digit addition and multiplication: Evidence from EEG oscillations in theta and lower alpha bands. *International Journal of Psychophysiology*, *128*, 81-92.

Zhu, R., Luo, Y., You, X., & Wang, Z. (2018). Spatial bias induced by simple addition and subtraction: From eye movement evidence. *Perception, 47*, 143-157.

Table 1. *Mean solution times (and standard deviations) as a function of operation (Add. for Addition and Mult. for Multiplication), type of problems, SOA and age group as well as priming effects.*

Operation	Type	Older adults		Younger adults		Priming effect	
		Null SOA	-150 SOA	Null SOA	-150 SOA	Older	Younger
Add.	Tie	839 (120)	815 (119)	729 (120)	709 (119)	24^{ns} (98)	20^{ns} (97)
	Large	974 (149)	931 (167)	940 (149)	911 (167)	43* (64)	29** (66)
	Small	846 (121)	791 (125)	782 (121)	751 (125)	55* (59)	31*** (61)
	With 0	953 (129)	928 (147)	738 (129)	741 (147)	25^{ns} (81)	$–3^{ns}$ (82)
	With 1	784 (105)	750 (86)	725 (105)	670 (86)	34***(68)	55* (66)
Mult.	Tie	840 (110)	807 (98)	714 (110)	709 (98)	33^{ns} (76)	5^{ns} (76)
	Large	963 (183)	943 (188)	952 (183)	958 (188)	20^{ns} (72)	$–6^{ns}$ (71)
	Small	868 (164)	837 (126)	809 (164)	790 (126)	31^{ns} (76)	19^{ns} (76)
	With 0	952 (151)	951 (176)	710 (151)	707 (176)	1^{ns} (81)	3^{ns} (82)
	With 1	833 (113)	842 (130)	686 (113)	683 (130)	$–9^{ns}$ (76)	3^{ns} (76)

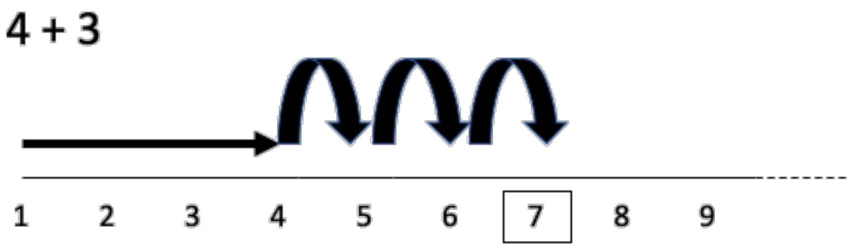

Figure 1. Schematic representation of the use of an automated procedure for the problem

4 + 3

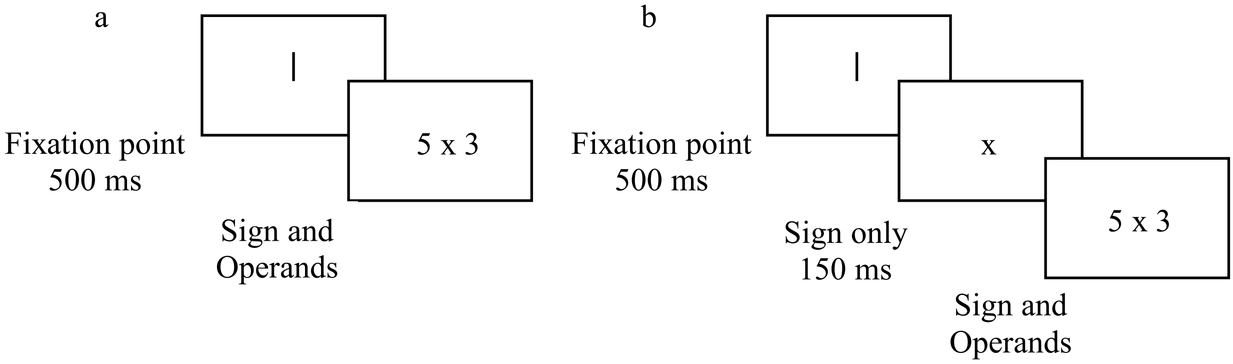

Figure 2. Examples of trial sequences for multiplication (a) in the null SOA and (b) the– 150 SOA conditions