Impact of aging on problem size and proactive interference in arithmetic facts solving

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Abstract

Arithmetic facts (AF) are required when solving problems such as "3x4" and refer to calculations for which the correct answer is retrieved from memory. Currently, two important effects that modulate the performance in AF has been highlighted: the problem size effect and the proactive interference effect. The aim of the present study is to investigate possible age-related changes of the problem size effect and the proactive interference effect in AF solving. To this end, the performance of young and older adults was compared in a multiplication production task. Furthermore, an independent measure of proactive interference was assessed to further define the architecture underlying this effect in multiplication solving. The results indicate that both young and older adults were sensitive to the effects of interference and of the problem size. That is, both interference and problem size affected performance negatively: the time needed to solve a multiplication problem increases as the level of interference and the size of the problem increases. Regarding the effect of aging, the problem size effect remains constant with age, indicating a preserved AF network in older adults. Interestingly, sensitivity to proactive interference in multiplication solving was less pronounced in older than in younger adults suggesting that part of the proactive interference has been overcome with age.

Keywords: Proactive interference, Problem size, Aging, Arithmetic facts, Numerical cognition

Introduction

Arithmetic facts (AF) refer to calculations for which the correct answer is retrieved from memory rather than calculated. Numerical problems (operands and answers) of AF, such as “3x4”, are assumed to be stored in interconnected associative networks in long-term memory (e.g., Ashcraft, 1992; Campbell, 1995; Verguts & Fias, 2005). Importantly, they are required for many everyday life situations: for instance, to make a recipe or to pay at the store, and are considered as the basis of more complex calculations. Given the high incidence of arithmetic difficulties throughout development, the acquisition of AF received much attention (e.g. Geary, 1993; Jordan & Montani, 1997). However, although fundamental, only a handful of studies (e.g. Geary & Wiley, 1991) investigated the impact of normal aging on AF solving.

A robust observation regarding AF is the modulation of the performance by the size of the problem when solving AF, i.e. the problem size effect (e.g. Stazick, Ashcraft, & Hamann, 1982; De Brauwer, Vergus, & Fias, 2006; Campbell, 1995; for a review, see Zbrodoff & Logan, 2005). The problem size effect indicates that small problems (e.g. 2 x 3) are solved faster and with fewer errors than large problems (7 x 8). This effect is assumed to reflect a memory retrieval component of processing (Campbell & Graham, 1985; Campbell & Xue, 2001; Allen et al., 2005; LeFevre et al., 1996; Miller, Perlmutter, & Keating, 1984). A typical explanation of the problem size effect is that the strength of associations between operands and answers differs between AF in the network (Ashcraft & Guillaume, 2009; see also Allen et al., 2005): small problems present stronger associations in long-term memory and are therefore solved faster than large problems. Some authors suggested that the variation in the strength of these associations depends on the frequency of occurrence and usage of each numerical problem (Ashcraft 1982; 1987; Hammann & Ashcraft, 1986; Ashcraft & Christy, 1995; McCloskey & Lindemann, 1992). For example, Ashcraft & Christy (1995) reported that large problems are underrepresented in elementary school books compared to small problems.

Another explanation of the problem size effect was proposed in terms of differences in strategy selection between small and large problems (Penner-Wilger, Leth-Steensen, & LeFevre, 2002; LeFevre et al., 1996; Campbell & Xue, 2001, Imbo & Vandierendonck, 2008; for a review see Zbrodoff & Logan, 2005). More specifically, small problems would be more often solved using retrieval strategies than large problems. In other words, the use of procedural strategies, which are considered as less efficient, would be more frequently used for large than for small problems.

Regarding the effects of aging, previous studies on AF solving mainly reported similar problem size effects between young and older adults (e.g., Geary & Wiley, 1991; Geary, Frensch, & Wiley, 1993; Allen, Smith. Jerge, & Vires-Collins, 1997; Allen et al., 2005). For instance, using multiplication production and verification tasks, Allen et al., (1997) demonstrated that only peripheral processes (i.e. encoding and response execution) varied across ages. Older adults were slower in encoding problems and executing responses than young adults. In contrast to peripheral processes, age-related invariance is observed for the problem size effect. A similar pattern of results was found with addition operations (Geary & Wiley, 1991), as well as with subtraction operations (Geary et al., 1993). Based on these findings, it was argued that age-related differences mainly concerned peripheral processes but not fact retrieval *per se*, suggesting an intact AF network in older adults.

A recent study (De Visscher & Noël, 2014) highlighted another important factor influencing the performance in AF: the proactive interference parameter. This parameter is believed to measure the proactive interference that is progressively set throughout the learning of multiplication tables. According to these authors, the previously learned problems disturb the learning of new problems (i.e. proactive interference). This proactive interference would occur because of the physical similarities between the old and the new problems. These physical similarities come from the analogous associations of digits (i.e. the combination of the digits 0 to 9) composing all AF. Problems that have more similar associations of digits with the previously learned problems would be more difficult to memorize.

Concretely, the proactive interference parameter was computed by measuring the number of similar associations between a given problem and previously learned problems. For example, when learning the multiplication 3 x 9 = 27, the different combinations of two digits for this problem are: 2-7, 2-3, 3-9, 3-7, 9-2 and 9-7. According to the learning order from table 2 up to table 9, the combination of digits 2–7 has already been encountered in two previously learned problems (**2** x**7** = 14 and 3 x **7** = **2**1) and therefore 2 points are added to the proactive interference score of that problem. The combination of the digits 3-2 has been found in four previously learned problems (**2** x **3** = 6, 4 x **3** = 1**2**, **3** x 7 = **2**1 and **3** x 8 = **2**4) and hence 4 points are added to the proactive interference score. Similarly, the combinations of digits 3-9 (**3** x **3** = **9**), 3-7 (**3** x **7** = 21) and 9-2 (**2** x **9** = 18) have been found in one previously learned problem and respectively add 1 point to the proactive interference score. Finally, the combination of the digits 7-9 has not been found in any of the previously learned problems and so no point is added. In sum, the total score of proactive interference for the multiplication 3 x 9 equals 27 is 7 (for further details, see De Visscher & Noël, 2014). In sum, the proactive interference parameter provides a quantitative measure of the proactive interference weight for each multiplication by measuring the overlap of digits between that problem and the previously learned ones.

The authors' results showed that beyond the size effect, the effect of interference substantially determined the performance across multiplication problems, meaning that the time to solve a multiplication increases as the level of proactive interference increases. This effect of interference has been observed in children as well as in young adults (De Visscher & Noël, 2014; see also De Visscher, Berens, Keidel, Noël & Bird, 2015).

To our knowledge, no study has currently investigated the evolution of proactive interference with age in AF solving. In the non-numerical domain, it has repeatedly been observed that older adults have more difficulty resolving proactive interference in memory tasks (e.g. Jonides et al., 2000; Thompson-Schill et al., 2002; Chiappe, Siegel, & Hasher, 2000; May, Hasher & Kane MJ, 1999; Loosli, Rahm, Unterrainer, Weiller, & Kaller, 2014). For instance, Jonides et al., (2000) compared age-related changes in proactive interference via the recent probes task (Monsel, 1978). In this task, participants have to memorise a set of items (target set of trial n; e.g. "a b c d"). Subsequently, a probe is presented and participants have to decide whether it was one of the memorised items of that trial. This probe can either require a positive response (e.g. "a") because it was a member of the target set (positive probes) or require a negative response (e.g. "e") because it was not a member of the target set (negative probes). Some negative probes (e.g. "f") were presented at the previous target set (trial n-1 ; e.g. "f g h i") producing proactive interference (they are called, recent negative probes) while the other negative probes (e.g. "k") were not recently presented. Jonides et al., (2000) demonstrated that the difference in performance between the recent negative probes and the non-recent negative probes was larger for older adults, suggesting a higher sensitivity to proactive interference with age.

The main aim of the current study was to examine the impact of normal aging on AF solving by investigating both the problem size effect and the proactive interference effect. Related to this purpose, we explored whether the above-mentioned proactive interference parameter was still playing a role in older adults, and whether AF were affected by the increase of sensitivity to interference with aging. To that aim, we used an independent measure of sensitivity to proactive interference to further define the architecture underlying the proactive parameter in multiplication solving. We compared the performance of participants from two different age groups (young and older adults) in a multiplication production task and in a recent probes task. We hypothesized that both the problem size effect and the proactive interference effect would determine the performance in AF solving in both groups. Considering previous studies (Geary & Wiley, 1991; Geary et al., 1993; Allen et al., 1997; Allen et al., 2005), we expected a similar problem size effect between older and young adults. Concerning the proactive interference effect, De Visscher and Noël (2014) argued that proactive interference is taking place during the developmental stage when children are learning the AF. Based on this argument, the amount of proactive interference can be expected to be the same or even smaller in older compared to younger adults as the time interval between the creation of the AF network and the moment of testing is by definition longer in older compared to younger adults. Because the AF network of older adults is built since a long time ago and may have surmounted a part of this proactive interference effect. Alternatively, if the amount of proactive interference relates to overall sensitivity to interference (e.g. Jonides et al., 2000) rather than to the passage of time since the learning of the arithmetic facts, one can expect stronger proactive interference effects in older compared to younger adults.

Method

Participants

A total of 48 participants took part in the present study: 24 young adults between 20 and 35 years, and 24 healthy older adults between 55 and 75 years. Each volunteer was paid 8 euros for their participation. The study protocol was approved by the local ethical committee. All participants were naïve with respect to the purpose of the experiment. Participants with dementia, alcoholism, low level of education (at least primary education), history of stroke, head trauma, metabolic disorder, psychiatric disorder and general anaesthesia in the past 6 months were excluded. In the older adults, the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005) was used to assess global cognitive functioning in order to exclude subjects with potential risk of dementia (Moca score > 26). Moreover, the Geriatric Depression Scale was used to discard subjects with high depressive symptoms (GDS score > 10). All participants were French-speaking and had normal or corrected to normal vision.

Following the data acquisition and before the data analyses, 4 older adults were excluded because they did not meet the selection criteria presented above: 2 had a suspected cognitive impairment and 2 had suspected depressive symptoms. The final sample thus included 44 participants: 24 young adults (M = 24.5 years, SE = 0.75; 16 women [1 left-handed] and 8 men [2 left-handed]) and 20 older adults (M = 62.9 years, SE = 1.26; 12 women [1 left-handed] and 8 men [1 left-handed]). Young adults had more years of education than older adults, $t(41) = 3.04$, $p < .01$. The average level of education was 16 years (SE = 0.43 years) and 13.70 years (SE = 0.62 years) in young and older adults respectively. We therefore explored the relationship between the level of education and our variables of interest and no correlation was found [all $r < |.15|$, all $p > .350$].

Material and procedure

All the participants were submitted to a pool of tasks. Here, we report only the data for the multiplication production and recent probes tasks that are of interest to this study. Young and older adults were tested in a quiet room at the university or at home. All tasks were run on a 17-inch laptop computer, using Prime 2 Professional Software (Psychology Software Tools).

Multiplication production task

Participants were asked to solve the 36 multiplication problems from 2 x 2 to 9 x 9 (without the commutative pairs), including the 8 ties problems (e.g. 6 x 6). Following the method of De Visscher & Noël (2014), 14 of the non-tie problems started with the smaller operand and 14 started with the larger operand with a similar problem size (magnitude of the products) between both subsets. Multiplication problems were presented following a pseudo-random order, such that two successive problems never had the same answer or operand and that no more than three successive problems were of the same type (smaller operand first, larger operand first or tie problem). Each trial began with a fixation point (500 ms) followed by a multiplication problem displayed in Arabic format in black on a white background until a response was produced orally. The oral response removed the multiplication from the screen and the next trial started after a delay of 500 ms. A millisecond-accurate voice key was used to record vocal response latencies. Accuracy was recorded by the experimenter. Participants were instructed to answer as quickly and as accurately as possible.

Recent probes task

In the recent probes task, participants had to judge whether a probe was part of the target set previously presented. A trial started with a fixation point (500ms) followed by the target set. The target set consisted of four lowercase letters (Courier New font, size 50) arranged as a square (see figure 1). The target set remained on the screen for 2500 ms followed by a delay of 3000 ms. After this delay, a single letter probe was presented in the middle of the screen (Courier New font, size 50). Participants had to indicate, by pressing a left or a right-sided button on a response box, whether the letter belonged to the current target set or not. Participants were instructed to answer as fast and as accurately as possible. The maximum response time allowed was 1500 ms. After this delay or after a response, the next trial was initiated, with an inter-trial interval of 500 ms. On half of the trials, the probe required a positive response because it matched a member of the target set (positive trials; see figure 1a). On the other half, the probe required a negative response because it did not match any member of the target set (negative trials). Two types of negative trials were contrasted: in the recent negative trials, the probe did not match a target of the current target set but was a member of the previous target set (see figure 1b); in the non-recent negative trials, the probe did not match any targets from the current trial and has never been encountered before (see figure 1c). In total, the task included 80 trials consisting of 40 positive trials, 20 non-recent negative trials and 20 recent negative trials. One half of the participants had to press the left button for positive trials and the right button for negative trials, whereas for the other half this response mapping was reversed. The trials were pseudo-randomly presented with no more than 3 consecutive identical conditions. The letters were randomly chosen among the consonants with the restriction that the letters were not perceptually similar. According to a visual similarity matrix computed by Boles & Clifford (1989), 7 associations of letters (i.e. “db”, “dp”, “dq”, “qp”, “xk”, “qg” and “nm”) were excluded between the negative probe and the letters in the target set as well as between the letters within the target set. Finally, the arrangement of positive probes and recent negative probes was balanced between the 4 spatial positions of the target set.

Figure 1 about here

Data analyses

In the multiplication production task, the proactive interference parameter and the product were used as measures of the proactive interference and the size of the problems respectively. Data were analysed using both repeated-measures analyses of variance (ANOVA) and linear regressions. For the ANOVA analyses, a dichotomous assignment was used for each effect (low versus high interference and small versus large problem size). For the interference effect, the 36 multiplication problems were ordered according to the proactive interference parameter and the 18 least interfering were defined as “low interference” (proactive interference parameter of 7 or smaller) while the 18 more interfering were defined as “high interference” (proactive interference parameter from 8 to 25). For the problem size effect, the 18 multiplication problems with the smallest products were classified as “small” problems (products that were 25 or smaller) and the 18 multiplication problems with the largest products were classified as “large” problems (products from 27 to 81). In accordance with this assignment, a 2 x 2 factorial design was produced with 12 multiplications in small/low interfering problems as well as in large/high interfering problems conditions and with

6 multiplications in large/low interfering problems as well as in small/high interfering problems conditions (see Appendix for further details). Therefore, we used a repeated-measures ANOVA with Problem Size (2: small problems, large problems) and Proactive Interference (2: low proactive interference, high proactive interference) as within-subjects factor and Group (2: young adults, older adults) as between-subjects factor. The ANOVA analyses were performed on mean accuracy and the median of reaction times (RTs) of correct trials only.

For the linear regression analyses, the interference level and the problem size were coded continuously according to the proactive interference parameter and the product respectively. First, we ran a linear regression for each group with the median of RTs as dependent variable and the Problem Size and Proactive Interference parameter as independent variables. This analysis was used to investigate which predictors determine the difficulty across multiplications. Second, we performed separate regression analyses for each participant with RTs as dependent variable and problem size and the proactive interference parameter as predictors. The individual slopes for each independent variable reflect a measure of each individual's sensitivity to proactive interference and problem size whereas the individual intercepts reflect an individual measure of peripheral processes (Cerella, 1991). These measures were therefore used to examine age differences in sensitivity to proactive interference, problem size and peripheral processes.

In the recent probes task, we used a repeated-measures ANOVA with Condition (3: positive, non-recent negative and recent negative) as within-subjects factor and Group (2: young adults, older adults) as between-subjects factor. This analysis was performed on the mean accuracy and the median of RTs of correct trials only. In order to assess the proactive interference effect, the critical comparison was the difference in performance between the non-recent negative and recent negative condition. In order to obtain an individual measure of proactive interference that is not confounded with general processing speed, the sensitivity to proactive interference for each participant was computed as follows[1]:

$$Sensivity\ to\ interference = \frac{Median\ RT\ on\ recent\ negative\ trials\ minus\ Median\ RT\ on\ non-recent\ negative\ \ trials}{Median\ RT\ on\ non-recent\ negative\ trials}$$

This measure was used to directly compare the sensitivity to proactive interference between young and older adults. Finally, a Bayesian analysis (Eidswick, 2012) using JASP-software (Love et al., 2015) was conducted to confirm the null hypothesis in our effects of interest (for a complete interpretation of Bayes-factors (*BF*), see Wagenmakers, Wetzels, Borsboom & van der Maas., 2011).

Results

Multiplication production task

A repeated-measures ANOVA with Problem Size and Proactive Interference as within-subjects factor and Group as between-subjects factor was run separately on accuracy (percentage of errors) and median RTs of correct trials (for an overview of all results, see Table 1). In young adults, the average error rate was 11.29 % (*SE* = 1.69%) and the mean of median RTs was 1232 ms (*SE* = 38.43 ms). In older adults, the mean number of errors was 7.218 % (*SE* = 1.85%) and the mean of median RTs was 1037 ms (*SE* = 42.09 ms).

[1] Using the recent negative condition as the baseline yielded the same pattern of results.

Regarding the error rate, the repeated-measures ANOVA showed a main effect of Problem Size [$F(1, 42) = 62.01$, $p < .001$, $\eta_p^2 = .60$], indicating that participants were more accurate for small problems (error rate = 2.52%, *SE* = 0.65) than for large problems (error rate = 15.95%, *SE* = 2.04%). A main effect of Proactive Interference was also observed [$F(1, 42) = 32.10$, $p < .001$, $\eta_p^2 = .43$]. Low interfering problems were better performed than high interfering problems (low interfering problems: error rate = 4.67%, *SE* = 0.91%; high interfering problems: error rate = 13.80%, *SE* = 1.90%). The interaction between Proactive Interference and Problem Size was significant [$F(1, 42) = 18.69$, $p < .001$, $\eta_p^2 = .31$], showing that the Proactive Interference effect was larger in large problems (mean difference = 15.52%) than in small problems (mean difference = 2.74%). The main effect of Group did not reach significance level [$F(1, 42) = 2.71$, $p = .107$, $\eta_p^2 = .06$]. The interaction between Problem Size and Group was significant [$F(1, 42) = 4.61$, $p = .038$, $\eta_p^2 = .10$]. The Problem Size effect was significant in both groups ($p < .001$), but was larger in young (mean difference = 17.10%) compared to older adults (mean difference = 9.77%). No interaction between Proactive Interference and Group was observed [$F(1, 42) = 1.33$, $p = .255$, $\eta_p^2 = .03$]. The three-way interaction between Proactive Interference, Problem Size and Group was not significant ($p = .422$).

Table 1 about here

The same analysis on the median RTs of correct responses revealed a main effect of Problem Size [$F(1, 42) = 89.72$, $p < .001$, $\eta_p^2 = .68$]. Small problems were more rapidly solved than large problems (small problems: mean of median RTs = 1003 ms, *SE* = 23.05 ms; large problems: mean of median RTs = 1266, *SE* = 38.49 ms). The main effect of Proactive Interference was also significant [$F(1, 42) = 107.47$, $p < .001$, $\eta_P^2 = .72$]. Low interfering problems (mean of median RTs = 1006 ms, *SE* = 25.77 ms) were more rapidly solved than high interfering ones (mean of median RTs = 1264 ms, *SE* = 35.64 ms). The interaction between Problem Size and Proactive Interference was found [$F(1, 42) = 17.16$, $p < .001$, $\eta_P^2 = .29$], showing that the Proactive Interference effect was greater in large problems (mean difference = 348 ms) than in small problems (mean difference = 168 ms). There was also a significant effect of Group [$F(1, 42) = 11.78$, $p = .001$, $\eta_P^2 = .22$], indicating that young adults were slower than older adults in multiplication solving. The interaction between Problem size and Group was observed [$F(1, 42) = 10.71$, $p = .002$, $\eta_P^2 = .20$; see figure 2A]. The problem Size effect was significant in both groups ($p < .001$) but the mean difference between small and large problems was larger in young adults (mean difference = 355 ms) than in older adults (mean difference = 173 ms). The Proactive Interference effect significantly interacted with the factor Group [$F(1, 42) = 10.83$, $p = .002$, $\eta_P^2 = .21$; see figure 2B]. The Proactive Interference effect was significant in both groups ($p < .001$) but was larger in young adults (mean difference = 340 ms) than in older adults (mean difference = 176 ms). The three-way interaction between Proactive Interference, Problem Size and Group did not reach significance ($p = .560$).

Figure 2 about here

In a next step, we reanalyzed the data using a regression analysis to explore which factors (problem size and/or proactive interference parameter) determine the difficulty across multiplications. Multiple regressions with median of RT across problems as dependent variable and the Proactive Interference parameter and Problem Size as predictors were run for both groups (see Table 2). In young adults, the Problem Size as well as the Proactive Interference parameter were significant and showed high partial correlations and effect sizes. In older adults, the Proactive Interference parameter was significant and explained a substantial part of the variance in performance with a partial correlation of .54. The problem size factor was also significant. In line with the ANOVA analysis, both the Problem Size effect and the Proactive Interference effect substantially determined the performance in multiplication solving.

Finally, we performed separate regression analyses for each person with the RTs as the dependent variable and the Problem Size and Proactive Interference parameter as predictors. The individual slopes for each independent variable were then used to examine Group differences in sensitivity to Problem Size and to Proactive Interference. In agreement with the ANOVA analysis, independent samples *t*-tests revealed that older adults were less sensitive to Proactive Interference than young adults [$t(42) = -2.68$, $p = .010$]. In contrast with the ANOVA analysis, independent samples *t*-tests revealed that older adults were equally sensitive to Problem Size than young adults [$t(42) = -1.36$, $p = .181$]. In order to confirm that this null result denotes an absence of age-related difference in peripheral processes (null hypothesis), we performed a Bayesian independent samples t-test. A BF_{10} of 0.624 was observed providing anecdotal evidence for similar problem size effect between both groups. When the peripheral processes and the proactive interference are taken into account, the problem size effect remains constant with age. Given the partial overlap between both effects, the results obtained in the ANOVA analysis for the problem size effect is probably driven by the proactive interference effect.

Regarding the peripheral processes, we compared the indivual intercepts in order to investigate group differences. Surprisingly, independent samples *t*-tests showed no significant Group effect in peripheral processes [$t(42) = 0.19$, $p = .849$]. A Bayesian independent samples t-test. A BF_{10} of 0.303 was observed providing substantial evidence for the null hypothesis. This results supports similar peripheral processes between both groups.

In summary, we found no evidence for a decay in arithmetical facts with aging. On the contrary, compared to young participants, older adults were faster, more accurate, less sensitive to the level of Proactive Interference and equally sensitive to the Problem Size when solving single-digit multiplications.

Table 2 about here

Recent probes task

A repeated-measures ANOVA with Condition (Positive, recent negative, non-recent negative) as within-subjects factor and Group as between-subjects factor was performed separately on accuracy (percentage of errors) and on median RTs of correct trials. The average error rate and the mean of median RTs by Condition for each Group are provided in Table 3. Overall error rate was on average 8.75% (*SE* = 1.72%) and 5.21% (*SE* = 1.57%) for older and young adults respectively.

Table 3 about here

Analysis of errors revealed a main effect of Condition [$F(2, 84) = 14.00$, $p < .001$, $\eta_p^2 = .25$]. Post-hoc comparisons with Bonferroni correction showed that more errors were produced in the recent negative condition compared to the non-recent negative condition ($p = .004$) indicating a Proactive Interference effect (recent negative condition: error rate = 7.62%, *SE* = 1.63%; non-recent negative condition: error rate = 3.69%, *SE* = 0.93%). The main effect of Group was not significant [$F(1, 42) = 2.31$, $p = .136$, $\eta_p^2 = .05$]. The interaction between Condition and Group was not significant either [$F(2, 84) = 1.18$, $p = .313$, $\eta_p^2 = .03$]. Even though the interaction between Condition and Group was not significant, we decided to perform a planned comparison to directly compare the performance in the non-recent negative condition with the performance in the recent negative condition. This more direct measure of the difference in proactive interference effect between both age groups was not significant [$F(1, 42) = 0.51$, $p = .478$, $\eta_p^2 = .01$]. Note that error rates were overall relatively low making it possible that ceiling performance obscured age related differences in performance.

Analysis of RTs showed that that the main effect of Condition was significant [$F(2, 84) = 6.04$, $p = .004$, $\eta_p^2 = .13$]. Post-hoc comparisons with Bonferroni correction revealed that recent negative trials were responded slower than non-recent negative trials ($p < .001$), indicating a significant proactive interference effect (recent negative condition: mean of median RTs = 794 ms, *SE* = 19.92 ms; non-recent negative condition: mean of median RTs = 751 ms, *SE* = 21.27 ms). The main effect of Group was also significant [$F(1, 42) = 21.11$, $p < .001$, $\eta_p^2 = .33$]. Older adults (mean of median RTs = 857 ms, *SE* = 28.90 ms) were globally slower than younger adults (mean of median RTs = 678 ms , *SE* = 26.38 ms). The interaction between Condition and Group failed to reach significance [$F(2, 84) = 0.42$, $p = .655$, $\eta_p^2 = .01$; see figure 3]. The Bayesfactor model comparison yielded evidence for an absence of interaction between Condition and Group. The best model was the additive model (with main effects of both Condition and Group but with no effect of interaction Condition x Group). This model was preferred by a factor of 6.192 over the full model (with both main effects and an interaction).

Figure 3 about here

We further evaluated the age effect in the sensitivity to interference by directly comparing the individual measures of proactive interference between the 2 groups. Confirming the results of the repeated-measures ANOVA, independent samples *t*-tests showed no significant Group effect in sensitivity to proactive interference [$t(42) = 0.45$, $p = .655$]. We performed a Bayesian independent samples t-test in order to confirm the null hypothesis A BF_{10} of 0.326 was observed providing substantial evidence for the null hypothesis. This supports that the sensitivity to proactive interference did not differ between young and older adults.

Relation between the sensitivity to proactive interference in numerical and non-numerical domain

Pearson's correlation between the individual sensitivity to proactive interference in multiplication solving and in recent probes task was carried out for all subjects. No correlation was found [$r(44) = .05$, $p = .724$; see figure 4]. A BF_{10} of 0.200 was observed for this correlation, indicating substantial evidence in favour of the null hypothesis.

Figure 4 about here

Discussion

The main aim of the present study was to investigate possible age-related changes of the problem size effect and the proactive interference effect in AF solving. To this end, the performance of young and older adults was compared in a multiplication production task. Furthermore, an independent measure of proactive interference was assessed using a recent probes task with letters to further define the architecture underlying the proactive interference effect in multiplication solving.

In the multiplication production task, the results including both an ANOVA and regression analyses showed that the performance in AF solving was influenced by both the problem size effect and the proactive interference effect in older adults. Replicating previous findings (De Visscher & Noël, 2014), the same pattern of results is observed in young adults. The problem size effect was robustly observed in young and older adults meaning that in the two groups, RTs and error rates increased as the size of the problem increased. Furthermore, the problem size effect observed in older adults was similar as the one observed in younger adults when peripheral processes and proactive interference were taken into account. In sum, retrieval of AF from long-term memory was not affected by aging. This conclusion is consistent with previous studies observing equal effect sizes between young and older adults (Geary & Wiley, 1991; Geary et al., 1993; Allen et al., 1997; Allen et al., 2005).

Regarding the proactive interference effect, to our knowledge, no study has yet examined it in the context of multiplication solving in older adults. The results showed that the proactive interference parameter substantially determined the performance across multiplication problems in young adults, thus replicating previous results described in the literature (De Visscher & Noël, 2014; De Visscher et al., 2015), but also in older adults, with greater interference leading to longer RTs and to larger error rate. Moreover, the comparison of sensitivity to proactive interference between both groups revealed that older adults were less sensitive to interference than younger adults. The proactive interference parameter represents the proactive interference weight for each multiplication based on the physical similarity of digits between a new problem to store and the previously learned ones. This proactive interference effect is believed to be decisive at the encoding stage, when children were learning multiplication tables (De Visscher & Noël, 2014). Corroborating this assumption, our results indicate that the proactive interference effect continues to impact multiplication performance into adulthood but progressively decreases its impact with age, probably due to the growing gap with the moment of AF acquisition: because AF network of older adults is established since a long time, they have overcome a part of the proactive interference effect. Besides this developmental explanation, the weaker sensitivity to proactive interference observed in older adults could also be related to differences in strategy selection. That is, due to differences in educational practices, older adults may have used the retrieval strategy more frequently/efficiently than younger adults. Note however, that such explanation hold can only be validated if future studies can demonstrate that a relation exists between strategy use and the proactive interference parameter.

In the recent probes task with letters, results indicated that both young and older adults were sensitive to proactive interference. Contrary to earlier observations (e.g. Jonides et al., 2000), this effect did not differ between older and young adults. Furthermore, no relation was found between the sensitivity to proactive interference in the letter task and in the multiplication task. A possible explanation for the absence of this relation is that the origin of proactive interference is different in both tasks. Indeed, the proactive interference in the multiplication task arises from the storage of AF and as a consequence, from long-term memory. Conversely, proactive interference comes from short-term memory in the recent probes task.

On the other hand, recent studies found such relation in a single case study of a person suffering from specific and developmental arithmetic fact retrieval deficits as well as in the comparison of children with good or weak AF network (De Visscher and Noël, 2013, 2014). Taken together with our results, it seems that this relation exists in developmentally young or in clinical populations but is not observed in non-clinical adult populations. Thus, the general capacity of resistance to proactive interference (with non-numerical material) would play a key role during the development of the AF network. In order to explain this pattern of results, we can use the analogy of constructing a building. The construction of a building requires the use of scaffoldings to support the walls. The use of scaffoldings will only be necessary during the process of construction and therefore its implication in the construction will be visible at this moment only. Once built, the scaffoldings are no longer necessary and its relation with the building will no longer be visible (for further details on this analogy, see Apperly, Samson, & Humphreys, 2009). Similarly, the general capacity of resistance to proactive interference seems to be involved in the development of the AF network, explaining the effect of the proactive interference parameter. Once AF are acquired, we continue to observe the specific effect of proactive interference in multiplication solving with the most interfering problems leading to longer RTs and to larger error rate. However, according to this view and in line with our results, the proactive interference in AF solving in adulthood should not be influenced by changes in the general capacity of resistance to proactive interference. Nevertheless, one could hypothesize that if we were teaching these participants new arithmetical facts, then, the influence of general capacity of resistance to proactive interference would become apparent again. However, even in those conditions, group differences might not be expected as the older participants did not show larger sensitivity to proactive interference than younger participants in the recent probe task.

In conclusion, this study shows that when solving multiplications, both young and older adults were sensitive to the effects of interference and of the problem size. That is, both interference and problem size affected performance negatively: the time needed to solve a multiplication problem increases as the level of interference and the size of the problem increases. Consistent with previous research (e.g. Allen et al., 2005), the problem size effect remains constant with age, indicating a preserved AF network in older adults. Interestingly, we also observed that the sensitivity to proactive interference in multiplication solving was weaker in older than young adults. Finally, our results suggest that the general capacity of resistance to proactive interference in adulthood is no longer involved in the proactive interference effect in numerical domain.

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Appendix.

Stimuli of the multiplication production task

Small Problem Size Low Interference	Small Problem Size High Interference	Large Problem Size Low Interference	Large Problem Size High Interference
2x2	3x4	5x6	4x7
2x3	3x8	6x6	4x9
2x5	4x5	7x5	5x8
2x8	6x3	9x5	6x8
2x9	6x4	7x7	6x9
3x3	7x3	9x9	7x6
4x2			8x4
4x4			8x7
5x3			8x8
5x5			8x9
6x2			9x3
7x2			9x7

Footnotes

[1] Using the recent negative condition as the baseline yielded the same pattern of results.

Figures and tables

Figure 1. Illustration of the design for the Recent probes task with an example for (a) the positive condition, (b) the recent negative condition and (c) the non-recent negative condition.

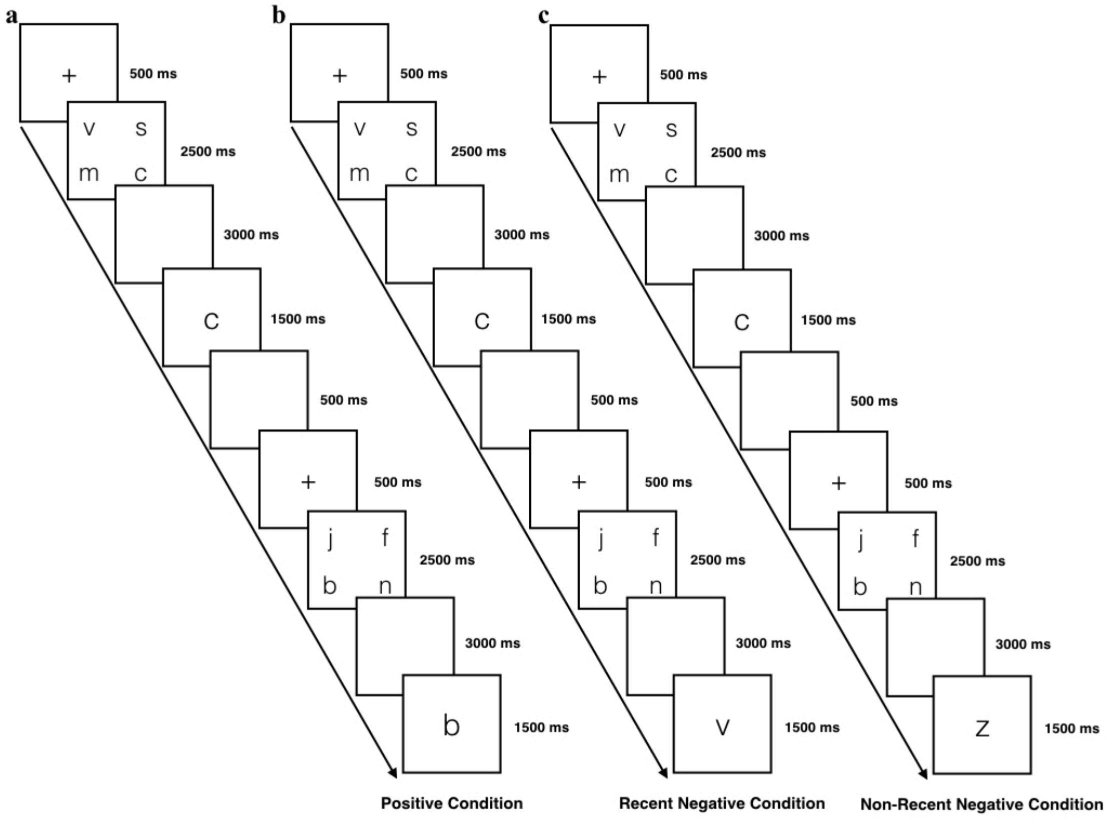

Figure 2. Mean of median RTs for (A) small and large problem sizes and for (B) low and high interference problems in young and older adults.

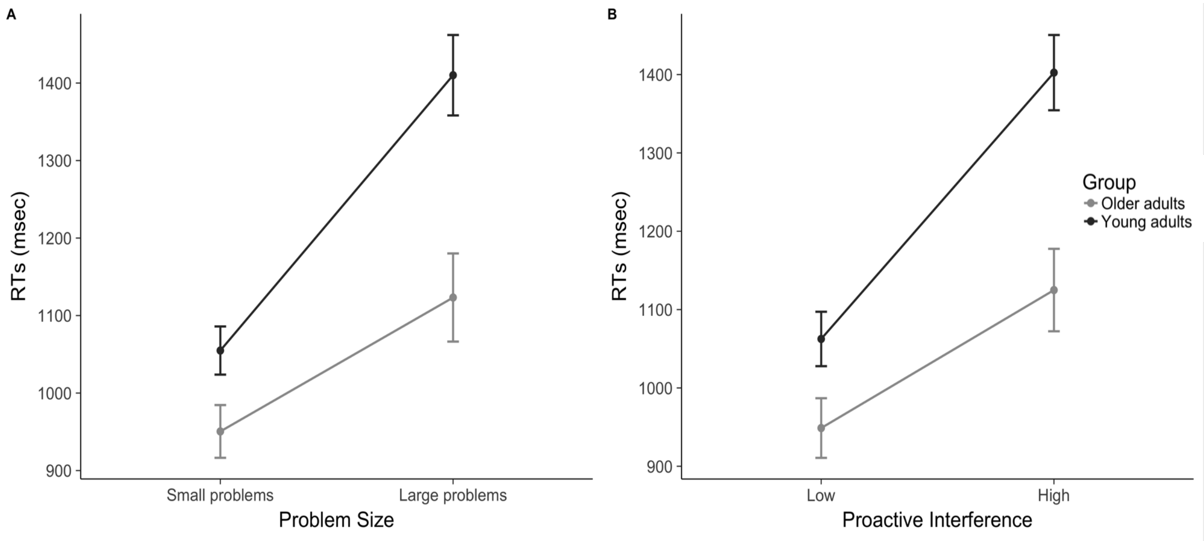

Table 1. Descriptive (average error rate in percentage and mean of median RTs in milliseconds) and inferential statistics for the Multiplication production task

Variables	Error rate (%)	Reaction times (ms)	Anova (error rate)	Anova (reaction times)
Problem Size				
Small	2.52	1003	$F(1, 42) = 62.01, p < .001, \eta_p^2 = .60$	$F(1, 42) = 89.72, p < .001, \eta_p^2 = .68$
Large	15.95	1266		
Proactive Interference				
Low	4.67	1006	$F(1, 42) = 32.10, p < .001, \eta_p^2 = .43$	$F(1, 42) = 107.47, p < .001, \eta_p^2 = .72$
High	13.80	1264		
Group				
Young adults	11.29	1232	$F(1, 42) = 2.71, p = .107, \eta_p^2 = .06$	$F(1, 42) = 11.78, p = .001, \eta_p^2 = .22$
Older adults	7.22	1037		
Proactive Interference x Problem Size				
Proactive Interference effect (high minus low) in small problems	2.74	168	$F(1, 42) = 18.69, p <.001, \eta_p^2 = .31$	$F(1, 42) = 17.16, p < .001, \eta_p^2 = .29$
Proactive interference effect (high minus low) in large problems	15.52	348		
Problem Size x Group				
Problem Size (large minus small) effect in young adults	17.10	355	$F(1, 42) = 4.61, p = .038, \eta_p^2 = .10$	$F(1, 42) = 10.71, p = .002, \eta_p^2 = .20$
Problem Size (large minus small) effect in older adults	9.77	173		
Proactive Interference x Group				
Proactive Interference effect (high minus low) in young adults	10.99	340	$F(1, 42) = 1.33, p = .255, \eta_p^2 = .03$	$F(1, 42) = 10.83, p = .002, \eta_p^2 = .21$
Proactive Interference effect (high minus low) in older adults	7.27	176		

Table 2. Multiple regressions on the mean of median RTs with the interference parameter and the problem size as predictors in young and older adults

REACTION TIME		Zero-order correlation	Partial correlation	*t*	P-value	β	R^2
Young Adults N = 24	Interference parameter	.70	.53	3.60	<.005	0.46	.62
	Problem size	.69	.51	3.39	<.005	0.43	
Older Adults N = 20	Interference parameter	.69	.54	3.66	<.005	0.51	.55
	Problem size	.61	.38	2.40	<.050	0.33	

Table 3. The average error rate (in percentage; with standard error) and the mean of median RTs (in milliseconds; with standard error) by Condition in young and older adults for the Recent probes task

	Error rate (%)						Reaction times (ms)					
	Positive		Non-recent Negative		Recent Negative		Positive		Non-recent Negative		Recent Negative	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Young Adults	8.75	1.83	1.87	1.25	5.00	2.20	672.25	29.45	663.33	28.68	697.17	26.87
Older Adults	10.50	2.01	5.50	1.37	10.25	2.41	842.55	32.27	838.70	31.42	890.85	29.43

Figure 3. Mean of median reaction times for positive, non-recent negative and recent negative conditions in young and older adults.

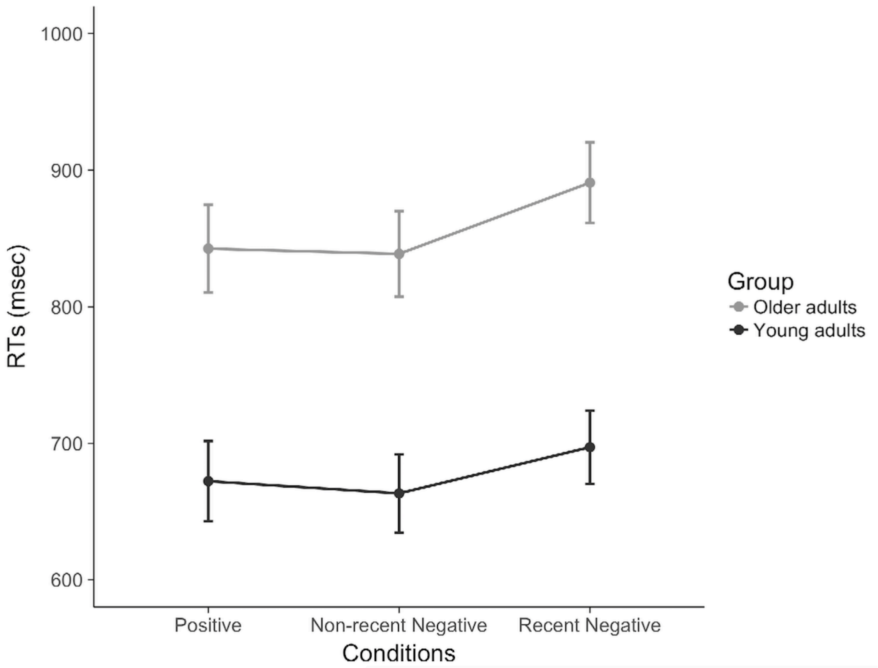

Figure 4. The absence of correlation between the sensitivity to proactive interference in the numerical and non-numerical domains. Scatter plot of the correlation between the sensitivity to proactive interference in multiplication production task (X-axis) and the sensitivity to proactive interference in recent probes task (Y-axis).