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How negative emotions influence arithmetic performance: a comparison of young and older adults

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Abstract
We investigated the influence of negative emotions on arithmetic problem-solving performance and age-related differences therein. Participants were asked to verify complex multiplication problems that were either true (e.g., $4\times26=104$) or false (e.g., $5\times41=201$). Half the problems were five problems (e.g., $5\times28=140$) and half were non-five problems (e.g., $6\times36=216$). False five problems violated the five-rule, the parity-rule, both rules, or no rule. Problems were preceded by emotionally neutral or negative pictures. For true problems, emotions impaired performance while verifying non-five problems in young adults only and while verifying five problems in older adults only. For false five problems, negative emotions influenced young adults' performance while verifying both-rule and no-rule violation problems but not when verifying parity-rule violation or five-rule violation problems. Negative emotions did not influence older adults' performance whichever false five problems they solved. These findings suggest that negative emotions may change the mechanisms that participants use to solve arithmetic problems and that emotions influence young and older adults via different mechanisms.

Keywords Aging · Arithmetic · Emotion · Cognition

Introduction

Do negative emotions influence arithmetic performance and does this influence change with age during adulthood? The few works that have studied the influence of emotions on arithmetic performance have shown that negative emotions impair arithmetic problem-solving performance. However, unknown is whether negative emotions change how participants solve problems and whether emotion effects occur similarly in young and older adults. One of the original features of the present study was to examine the influence of emotions on performance for different types of arithmetic problems and whether this influence changes with aging during adulthood. Based on previous research suggesting that participants use different strategies to solve different types of problems, finding age-related differences in how emotions influence participants' performance on different types of problems would suggest that the effects of emotions on arithmetic performance occur via different mechanisms in young and older adults. Before outlining the logic of the present work, we briefly review previous findings on arithmetic and on effects of negative emotions on arithmetic performance in young and older adults.

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Previous findings on arithmetic

Research in arithmetic aims at determining the crucial factors that influence arithmetic performance and at deciphering mechanisms responsible for how these factors exert their influence. Previous research found that characteristics of tasks, participants, stimuli, and situations influence arithmetic performance. For example, participants are faster when they are asked to accomplish verification tasks (e.g., $4+8=12$. True? False) than when they are asked to accomplish production tasks (e.g., $4+8=$?), when they solve tie problems (e.g., $6 \times 6 = 36$) compared to non-tie problems (e.g., $6 \times 7 = 42$) problems, when they are tested under lower-speed pressure conditions, and when their working-memory or other attentional resources are higher (see Cohen Kadosh & Dowker, 2015; Gilmore et al., 2018; Knops, 2020, for recent reviews).

One set of important findings relevant to the present work concerns the fact that participants use several strategies to solve different arithmetic problems and, when they use the same strategy, they execute it with different levels of speed and accuracy for different types of problems (e.g., Siegler, 2007). For example, when they are asked to verify true arithmetic problems participants use exhaustive verification strategies and are faster on five problems, such as $5 \times 16 = 80$, than on non-five problems, such as $6 \times 13 = 78$ (e.g., Campbell & Oliphant, 1992). They first encode the problem (operands and proposed solution), search (via either retrieval or calculation) the correct product, compare the proposed and the correct product, make true/false decision, and output their response. Finding the correct solution is easier and faster for five problems than for non-five problems, because basic arithmetic facts including 5 as an operand are more strongly and distinctively represented in long-term memory and more easily accessed. Of interest in the present study was whether negative emotions have similar or different effects on true, five and non-five problems. This was expected to determine whether effects of emotions influence execution of arithmetic strategies.

In contrast, when they verify false problems, participants sometimes use exhaustive verification strategies and sometimes fast non-exhaustive verification strategies (or heuristics). For example, they use an exhaustive verification strategy when they are asked to verify problems like $4 \times 12 = 46$, and they use a parity-rule violation checking strategy (i.e., to be true, a product must be even if either or both of its multipliers is even) when they are asked to verify problems such as $4 \times 12 = 49$. To reject a false arithmetic problem, participants quickly detect when an arithmetic rule is violated and provide a false response, without searching for the correct answer. Consequently, participants are faster on problems like $4 \times 16 = 63$ that violate the parity-rule than on problems like $4 \times 16 = 62$ that respect this parity-rule (Hinault, Tiberghien, et al., 2015). Also, they are faster when they verify problems like $5 \times 32 = 164$ that violate the five-rule (e.g., five-rule, $N \times 5 =$ a product that ends in 0 or 5; Lemaire & Reder, 1999; Lemaire & Siegler, 1995) or like $5 \times 32 = 163$ that violate both the parity and the five-rules (Hinault, Dufau, et al., 2015; Hinault, Tiberghien, et al., 2015). These fast, arithmetic-rule violation verification strategies vary in speed. For example, participants are faster on problems that violate the five-rule than on problems that violate the parity-rule. This is usually accounted for by assuming that problem features for detecting five-rule violation are more salient than problem features for detecting parity-rule violation, which leads participants to more quickly reject the former than the latter (Hinault, Dufau, et al., 2015; Hinault, Tiberghien, et al., 2015). In the present study, we examined whether negative emotions influence problems that violate different arithmetic rules similarly or differently. This was expected to determine whether effects of negative emotions on participants' performance vary with the type of strategies they use to solve different types of problems.

A final set of important findings for the present project concerns age-related differences and similarities in arithmetic. Arithmetic is one of the rare cognitive domains in which there are no or much smaller age-related decrease in participants' performance (see Uittenhove & Lemaire, 2014, 2018, for overviews). Despite similar levels of arithmetic performance in young and older adults (and sometimes even better performance in older adults), previous research found that young and older adults can differ in which strategy they use, as well as how they select and execute arithmetic strategies (see Lemaire, 2016, for an overview). For example, Hinault and Lemaire (2017) asked young and older adults to verify arithmetic problems that violated or respected the five-rule, the parity-rule, or both-rules. Both young and older adults verified problems violating the parity-rule and the five-rule more quickly than problems violating no-rule. Also, both age groups had better performance when both the five and parity-rules were violated than when only one rule or no rules were violated. The benefits associated with two-rules violation problems were smaller in older than in younger adults (see also Hinault et al., 2015). Hinault and Lemaire proposed that smaller benefits on problems violating both rules in older than in younger adults stemmed from older adults not using both-rules violation verification strategy as systematically and as often as young adults and/or executing it less efficiently. Whether negative emotions influence young and older adults' performance similarly or differently while verifying arithmetic problems that violate arithmetic rules was tested in the present study.

In sum, previous findings showed that (a) arithmetic performance varies as a function of problem type (with five problems being solved more quickly than non-five problems, and with problems violating arithmetic rules being verified more quickly than problems violating no rules) and (b) similar age-related arithmetic performance associated with age-related differences in strategic aspects of arithmetic performance. These findings were considered in the present study on age-related differences in how emotions influence arithmetic performance.

Previous findings on effects of negative emotions on arithmetic performance

The influence of negative emotion on cognition has been documented in a wide variety of cognitive domains (see Lemaire, 2022, for overviews). Previous studies found that emotions can either improve (e.g., better recall performance for negative compared to neutral items; Kensinger & Kark 2018) or decrease (e.g., poorer recall performance under stress condition; Kirschbaum et al., 1993) performance depending on whether the emotion is relevant or not for the target task.

Attentional capture has been assumed as one of the responsible mechanisms for effects of negative emotion. Negative information more readily capture people's attention than other types of information (e.g., Yiend et al., 2013) and detracts participants' attention away from the target task. In contrast, better performance is found under negative emotion condition when negative emotions are relevant to the task as it directs attentional resources to deeper information processing (e.g., Blanchette et al., 2014). Despite a large number of investigations on the role of emotions in a wide variety of cognitive domains, much fewer studies have examined this role in arithmetic, and even fewer have examined how this role changes with age during adulthood.

Only a few studies examined the role of emotions in arithmetic (Fabre & Lemaire, 2019; Framorando & Gendolla, 2018; Kleinsorge, 2009; Lallement & Lemaire, 2021; Liu et al., 2021; Schimmack, 2005). For example, Lallement and Lemaire (2021) asked young and older adults to verify one-digit addition problems (e.g., $8+4=13$. True? False) in a first experiment and to estimate the results of two-digit multiplication problems (e.g., which estimate between 3200 and 4500 is closest to correct product for 42×84?) in a second experiment. In both experiments, problems were displayed superimposed on emotionally neutral (e.g., mushrooms) or emotionally negative (e.g., a corpse) pictures. In both simple and complex arithmetic, young and older adults obtained poorer arithmetic performance under negative emotion conditions. Most interesting, deleterious effects of negative emotions on arithmetic performance were larger in young than in older adults. Like in other cognitive domains, the authors usually explain these deleterious effects on arithmetic performance as a result of attentional capture. Negative emotions would capture young and older adults' attentional resources and would detract participants' attention away from the target arithmetic problem-solving task. However, this assumes that participants use the same arithmetic problem-solving strategies under negative and neutral emotion conditions. It is possible that above and beyond (or as a result of) attentional capture, participants use different strategies under emotionally negative and neutral conditions. As a consequence of negative emotions leading them to use poorer strategies, participants would obtain poorer performance under negative emotions. The present experiment aimed at testing this hypothesis.

Overview of the present experiment

This study had two main goals. First, we examined how negative emotions influence arithmetic problem-solving performance, and determined whether this influence is modulated by different problem types. Second, we examined age-related differences in how emotions influence arithmetic performance. Young and older participants were asked to verify true and false arithmetic problems under negative and neutral emotion conditions. Different problem types were tested depending on whether they were true or false problems, five or non-five problems, and whether proposed answers violated the parity-rule, the five-rule, or both-rules.

Above and beyond replicating previous findings showing effects of problem types on arithmetic performance (Hinault, Dufau, et al., 2015; Hinault, Tiberghien, et al., 2015; Hinault & Lemaire 2017; Lemaire & Siegler, 1995) and impaired performance under negative emotions (e.g., Fabre & Lemaire, 2019; Kleinsorge, 2007, 2009; Lallement & Lemaire, 2021; Liu et al., 2021; Schimmack, 2005), the present data were collected to test two hypotheses. One hypothesis concerned effects of emotions as a function of problem type and the other age-related differences in these effects.

First, we tested the hypothesis that effects of negative emotions interact with problem types. In other words, we hypothesized that negative emotions change the way participants verify arithmetic problems. Given prior findings in arithmetic showing that five problems are easier than non-five problems (e.g., Campbell & Oliphant 1992), larger deleterious effects of negative emotions were expected on true, non-five than on true, five problems. This was expected because, although both types of problems are known to be verified with an exhaustive verification strategy involving a series of processes (i.e., encoding, searching for sums via either calculation or retrieval, comparing correct and proposed sums, deciding true/false, and responding), non-five problems require more resources than five problems. With fewer resources available under negative emotions, participants were expected to be more impaired by negative emotions while solving non-five than five problems.

Also, we expected that deleterious effects of negative emotions on arithmetic performance would depend on whether false problems violated rules or not, and on the type of violated rules. Thus, largest effects of emotions were expected on problems violating no-rule compared to problems violating rules, because these problems are solved like true problems via the most demanding exhaustive verification strategies. Moreover, deleterious effects of negative emotions were expected to be larger on problems violating one rule than on problems violating two-rules, because two-rule violation problems are the easiest to solve and require fewer resources. Also, following previous findings of better performance on five-rule violation problems than on parity-rule violation problems (Hinault, Dufau, et al., 2015; Hinault, Tiberghien, et al., 2015), we expected larger deleterious effects of emotions on performance for parity-rule violation problems than for five-rule violation problems, and smallest effects on easiest, two-rule violation problems.

Second, we tested the hypotheses that effects of negative emotions on problem verification performance change with aging during adulthood. More specifically, given the robust age-related positivity effects (Mather, 2012; Mather & Carstensen, 2005; Reed et al., 2014; Reed & Carstensen, 2012), we expected that older adults were less influenced by negative emotions than young adults when they accomplished arithmetic problem-solving verification tasks, replicating previous age-related differences (Fabre et al., 2022; Lallement & Lemaire, 2021). Most original, given well-known age-related differences in cognitive strategies (see Lemaire, 2016 for an overview), the present study went one step further by testing the hypothesis that negative emotions influence different strategic aspects of arithmetic performance in young and older. This would happen if age-related differences in effects of negative emotions is not the same for different problem types. For example, emotions may influence rule-violation problems differently in young and older adults. In other words, in addition to smaller influence of negative emotions on older adults' verification performance, we tested the possibility that this influence interacts with problem types (five/no-five; rule-violation/no-violation problems).

Method

Participants

We recruited 68 participants online on Prolific (www.prolific.co), 33 young adults (15 females; *mean age*: 26.0 years; *range*: 22—30 years) and 35 older adults (22 females; *mean age*: 69.3 years; *range*: 65—78 years). Young and older adults were matched on education (mean number of years of formal education: 14.0 and 14.7, respectively, $F<1.0$). They were paid £7.5 per hour for their participation. Following previous studies on emotion and arithmetic (e.g., Fabre & Lemaire 2019; Lallement & Lemaire, 2021), where effect size of emotion on arithmetic performance ranged from 0.25 to 0.40, we used a $\eta^2 p=.25$ to determine sample size. With one between-participants factor (age) and three within-participants factors (Problem type, Rules violation, and Emotion), our design could achieve 95% power with 54 participants. In order to exceed this criterion, we recruited 68 (33 young and 35 older) participants. An informed consent was obtained from each participant prior to participation.

Material

Stimuli for the arithmetic problem verification task

Stimuli were the multiplication problems from Hinault et al. (2015). They were presented in a standard form ($a \times b=c$) with "a" as a single digit and "b" as a double digit or reversed (see Tables 1 and 2 in Supplemental Material). Single-digit operands ranged from 3 to 8 and two-digit operands ranged from 12 to 98. The set of 256 problems was presented once in a neutral condition and once in an emotional condition.

There were 128 five problems including 5 as an operand (e.g., 5×89=445) and 128 non-five problems not including 5 as an operand (e.g., 7×64=448). Half the five problems had an even non-five operand (e.g., 5×64=320), whereas the other half had an odd non-five operand (e.g., 5×93=465). The non-five problems had two even operands (even x even), two odd operands (odd x odd), or one even operand (even x odd or odd x even). Half the problems were true problems (e.g., 4×26=104), and half were false problems (e.g., 5×41=201). Proposed answers were correct products for true problems and incorrect products for false problems. Thus, there were 64 problems of each type (i.e., five true, five false, non-five true, non-five false problems). False problems respected or violated either the parity rule (i.e., a product must be even if either or both of its multipliers is even) or the five rule (i.e., $N \times 5$ product that ends in 0 or 5). This was possible by varying the differences between correct and proposed products. Proposed products for false non-five problems had splits between proposed and correct products of ±1, 2, 3, 4, 7, 9, 14, or 20. This resulted in half the false problems violating parity-rule (e.g., 6×17=103) and half respecting the parity-rule (e.g., 6×23=134). Four types of false five problems were tested: (1) parity-rule violation problems, with splits ±5 or ±15 between proposed and correct products (e.g., 5×12=65), (2) five-rule violation problems, with splits of ±2 or ±4 from correct products (e.g., 5×32=164), (3) parity- and five-rule violation problems, with splits of ±1 or ±3 from correct products (e.g., 5×31=158) and, (4) no-rule violation problems, with splits of ±10 or ±20 from correct products (e.g., 5×26=140).

Based on previous finding in arithmetic (see Cohen Kadosh & Dowker, 2015; Gilmore et al., 2018; Knops, 2020, for overviews), problems were selected so as to control the following factors: (1) no double-digit operand had 0 or 5 as

Table 1 Emotional valences (*mean, range; SD*) and arousal ratings for each type of problems

Elements	Negative	Neutral	*F(1,63)*
Emotional Valence			
True Five Problems (N=64)	2.91 (1.31 — 5.00; 1.02)	6.00 (5.24—6.84; 0.52)	464.87***
False Five Problems (N=64)	3.07 (1.49 — 4.92; 0.92)	6.04 (5.22—6.94; 0.52)	438.30***
True Non-Five Problems (N=64)	2.79 (1.51 — 5.16; 0.88)	6.23 (5.22 — 6.98; 0.53)	697.24***
False Non-Five Problems (N=64)	2.95 (1.45 — 5.07; 0.96)	6.18 (5.26 — 6.91; 0.47)	566.60***
F(3, 189)	0.97 (p = .409)	0.76 (p = .388)	
Arousal Rating			
True Five Problems	5.93 (4.47 — 7.26; 0.60)	4.37 (2.63 — 6.79; 0.93)	122.58***
False Five Problems	6.03 (4.02 — 6.35; 0.59)	4.24 (2.51 — 6.23; 0.80)	207.18***
True Non-Five Problems	5.99 (3.95 — 7.12; 0.73)	4.37 (2.6 — 6.41; 0.91)	182.78***
False Non-Five Problems	5.79 (4.48 — 7.29; 0.63)	4.59 (2.42 — 6.99; 0.97)	49.95***
F(3, 189)	1.73 (p = .163)	1.83 (p = .143)	

Notes. ***$p < .001$

unit digits (e.g., 30 or 35), (2) no double-digit operand had 5 as decade digit (e.g., 56), (3) no double-digit operand had the same unit digit as decade digit (e.g., 33), (4) the size and the side of double-digit operands were controlled, (5) size and direction of splits were matched across problems. The mean splits did not differ across five problems (*mean* = 7.0) and non-five problems (*mean* = 7.4), $F < 1.0$, (6) the magnitude of the proposed products did not differ between five problems (*mean* = 280) and non-five problems (*mean* = 285), $F < 1.0$. Furthermore, the mean magnitude of the proposed products did not differ between no-rule violation, five-rule violation, parity-rule violation, and both-rules violation problems (respectively 278, 281, 281, 280; $F < 1.0$). Finally, no false problems had proposed products equal to 100.

Stimuli for emotional pictures

Five hundred twelve pictures were selected from the International Affective Picture System (IAPS; Lang et al., 2008) depicting 256 negative events (e.g., mutilation) and 256 neutral events (e.g., candle). We selected negative pictures with the lowest valence ratings and the highest arousal ratings and neutral pictures with valence ratings and arousal ratings evenly split between negative and positive ratings. Each problem was paired with a neutral and an emotional picture. Emotional valence and arousal were matched across problem types (see Table 1). The pictures shown before and after arithmetic problems were the same in half the trials and different in the other trials. For different-picture trials, valence and arousal were the same for both pictures.

Procedure

The web extension E-prime Go controlled stimulus display, response recording, and collected response times with 1-ms accuracy. Each trial included one arithmetic problem and two pictures. On each trial, participants completed an arithmetic problem verification task and a picture comparison task. In the arithmetic problem verification task, they had to say whether the equation was true or false. In the picture comparison task, they had to say whether the pictures displayed before and after the arithmetic problem verification task were the same or different (see illustration of a trial in Fig. 1).

At the beginning of each trial, participants saw a blank screen for 400 ms, then a picture for 1500 ms, followed by a problem that was displayed on the screen until participants' response. Participants were instructed to press the "L" key on their keyboard if the problem is true and the "S" key if the problem is false, both with their index fingers. Response keys were counterbalanced across participants who had to solve the problems as quickly and accurately as possible. Next, a blank screen appeared for 500 ms, followed by a picture that was displayed for 1500 ms. The second picture was the same as the first picture in half the trials and different in the other trials. Participants had to press as quickly and as accurately as possible the "L" key if the pictures were the same or the "S" key otherwise. There were six practice trials followed by a total of 512 experimental trials divided into two blocks of matched problems (e.g., half the problems in a block were presented with a neutral picture and half with an emotional picture; half were true and half were false problems). Experiment lasted about 1.5 h, and participants had a break between each block. All problems were randomly presented within each block for each participant. Participants received feedbacks (i.e., percent errors) at the end of each block.

Results

Latencies larger or smaller than the mean of the condition $\pm$ 2.5 *SD*s were removed (2.3%). We examined how negative emotions influence participants' performance first while verifying true five and non-five problems then on false problems.

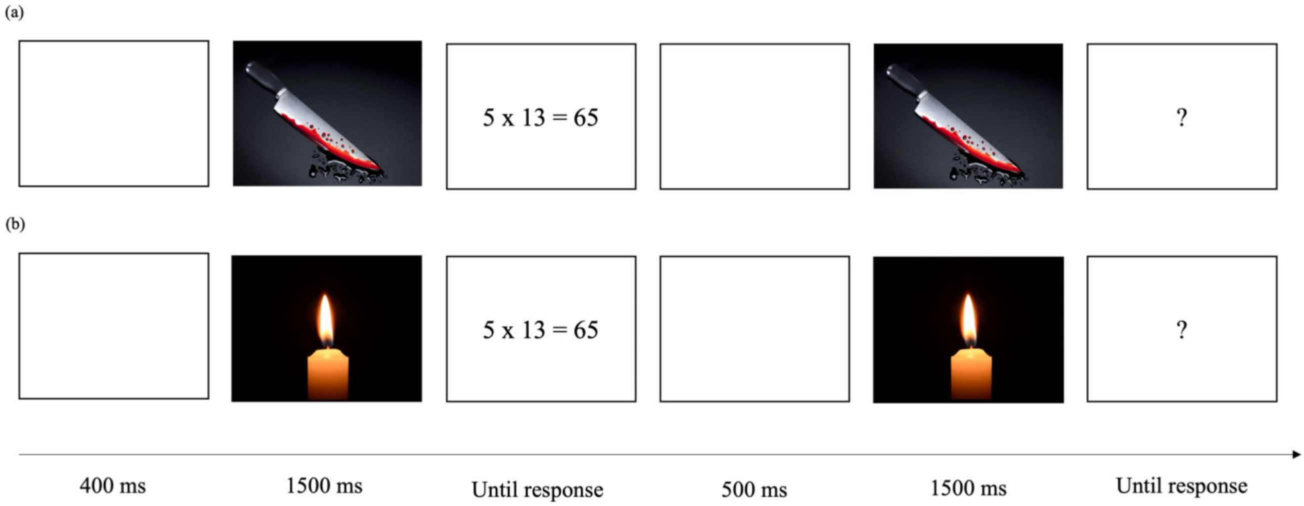

Fig. 1 Sequences of Events for a given trial. Participants had to decide whether the equation was true or false under negative emotion (a) or under neutral emotion (b), and then whether the pictures displayed before and after the arithmetic problems were the same or different

Table 2 Young and older adults' mean response times in ms (and percentages of errors) in neutral and negative emotion conditions while participants verified true arithmetic problems

	Negative	Neutral	*Means*	*Negative - Neutral*
Five Problems				
Young Adults	3808 (3.7)	3804 (4.0)	3806 (3.8)	4 (-0.3)
Older Adults	3222 (3.4)	3163 (3.6)	3193 (3.5)	59* (-0.2)
Non Five Problems				
Young Adults	4813 (11.5)	4622 (11.1)	4718 (11.3)	191* (0.4)
Older Adults	3752 (10.5)	3695 (9.8)	3724 (10.15)	57 (0.7)

Notes. *: $p < .05$

Effects of emotions on participants' performance while verifying true five and non-five problems

We first tested whether negative emotions modulate differences in performance between true five problems and true non-five problems in young and older adults. Mean verification times and percentages of errors were analyzed with mixed-design ANOVAs, 2 (Age: young, older adults) × 2 (Problem Type: five; non-five) × 2 (Emotion: negative; neutral), with age as the only between-participants factor (see means in Table 2).

Participants were faster in the neutral condition than in the negative emotion condition (3821 ms vs. 3899 ms; $F(1,66) = 8.29$, $p = .005$, $MSe = 413{,}986$, $\eta^2_p = 0.11$). The main effects of age, $F(1,66) = 9.43$, $p = .003$, $MSe = 4.39 \times 10^7$, $\eta^2_p = 0.13$, and of problem type, $F(1,66) = 87.02$, $p < .001$, $MSe = 3.53 \times 10^7$, $\eta^2_p = 0.57$, were qualified by a significant Age × Problem Type interaction, $F(1,66) = 6.09$, $p = .016$, $MSe = 2.47 \times 10^6$, $\eta^2_p = 0.08$. Participants were faster to respond on five problems compared to non-five problems (3499 ms vs. 4220 ms), and this difference was larger in young adults (3806 ms vs. 4718 ms) than in older adults (3193 ms vs. 3723 ms).

The only effect that came out significant on percentages of errors was the main effect of problem type, $F(1,66) = 110.38$, $p < .001$, $MSe = 3335.5$, $\eta^2_p = 0.63$, as participants made more errors on non-five problems than on five problems (10.7% vs. 3.7%).

No other effects came out significant on either verification times or percentages of errors.

Effects of emotions on participants' performance while verifying false five problems

Participants' mean latencies and percentages of errors on false five problems were analyzed with mixed-design ANOVAs, 2 (Age: young, older adults) × 2 (Emotion: negative; neutral) × 4 (Rule violation: no-rule violation; parity-rule violation; five-rule violation; two-rules violation problems) ANOVAs, with age as the only between-participants factor (see *means* in Table 3).

Young adults were slower than older adults (3675 ms vs. 3070 ms; $F(1,66) = 5.92$, $p = .018$, $MSe = 4.98 \times 10^7$, $\eta^2_p = 0.08$). The main effect of rule violation, $F(3,198) = 148.60$, $p < .001$, $MSe = 1.10 \times 10^8$, $\eta^2_p = 0.69$, and interacted with both the age factor, $F(3,198) = 2.83$, $p = .039$, $MSe = 2.11 \times 10^6$,

Table 3 Young and older adults' mean response times in ms (and percentages of errors) on each type of false five problems, in neutral and negative emotion conditions

Rule Violation	Negative	Neutral	*Means*	Negative - Neutral
Young Adults				
No rule	4689 (14.5)	4971 (15.2)	4830 (14.9)	-282* (-0.7)
Five-rule	3207 (2.3)	3262 (3.6)	3235 (3.0)	-55 (-1.3)
Parity-rule	3508 (6.4)	3482 (7.2)	3495 (6.8)	26 (-0.8)
Two-rules	3286 (2.5)	2998 (3.0)	3142 (2.8)	288* (-0.5)
Means	3673 (6.4)	3678 (7.3)	3675 (6.8)	-5 (-0.9)
Older Adults				
No rule	4610 (25.9)	4559 (23.6)	4585 (24.8)	51 (2.3)
Five-rule	2639 (5.2)	2567 (5.6)	2603 (5.4)	72 (-0.4)
Parity-rule	2787 (6.9)	2668 (6.5)	2728 (6.7)	119 (0.4)
Two-rules	2382 (6.5)	2347 (4.4)	2365 (5.5)	35 (2.1**)
Means	3105 (11.1)	3035 (10.0)	3070 (10.6)	70 (1.1)

Notes. *: $p<.05$; **: $p<.01$

$\eta^2_p = 0.04$, and the emotion factor, $F(3,198)=2.79$, $p=.042$, $MSe=459{,}438$, $\eta^2_p = 0.04$, were significant. Most interestingly, the Age × Rule violation × Emotion interaction, $F(3,198)=3.06$, $p=.029$, $MSe=503{,}526$, $\eta^2_p = 0.04$, came out significant. This interaction was further analyzed with within-participants 4 (Rule violation) × 2 (Emotion) breakdown analyses in each age group.

The Emotion × Rule violation interaction was significant in young adults ($F(3,96)=3.87$, $p=.012$, $MSe=913{,}308$, $\eta^2_p = 0.11$), but not in older adults ($F<1.0$). Young adults increased their speed while solving false, five, no-rule violation problems under negative emotions ($F(1,32)=4.90$, $p=.034$, $MSe=1.31\times10^6$, $\eta^2_p = 0.13$), but verified parity-rule violation ($F(1,32)=0.096$, $p=.759$, $MSe=11{,}551$, $\eta^2_p = 0.003$) and five-rule violation problems ($F(1,32)=0.189$, $p=.666$, $MSe=50{,}163$, $\eta^2_p = 0.006$) equally fast under neutral and negative emotion conditions. Moreover, young adults were slower on two-rule violation problems ($F(1,32)=4.40$, $p=.044$, $MSe=1.37\times10^6$, $\eta^2_p = 0.12$) under negative emotion condition than under neutral emotion condition. Older adults solved false five problems equally fast under negative and neutral emotion conditions, whether these problems violated no-rule ($F(1,34)=0.436$, $p=.513$, $MSe=46{,}445$, $\eta^2_p = 0.01$), parity rule ($F(1,34)=2.35$, $p=.134$, $MSe=247{,}807$, $\eta^2_p = 0.07$), five rule ($F(1,34)=0.871$, $p=.357$, $MSe=88{,}676$, $\eta^2_p = 0.03$), or both rules ($F(1,34)=0.218$, $p=.643$, $MSe=20{,}388$, $\eta^2_p = 0.01$).

Analyses of percentages of errors revealed a main effect of rule violation, $F(3,198)=45.72$, $p<.001$, $MSe=7627.8$, $\eta^2_p = 0.41$, which was qualified by an Age x Rule violation interaction, $F(3,198)=3.80$, $p=.011$, $MSe=633.9$, $\eta^2_p = 0.05$. In young adults, parity-rule violation effects were smaller than five-rule violation effects (8.0% vs. 11.9% ; $F(1,32)=9.13$, $p=.005$, $MSe=249.5$, $\eta^2_p = 0.22$) or two-rules violation effects (8.0% vs. 12.1%; $F(1,32)=8.73$, $p=.006$, $MSe=274.0$, $\eta^2_p = 0.21$). In older adults, effects of parity-rule violation, five-rule violation, and two-rule violation were all significant (Fs > 37.5, ps < 0.001).

General discussion

This study examined the role of negative emotions on arithmetic performance and determined whether this influence changes during adulthood with aging. Young and older adults were asked to verify five and non-five, true and false arithmetic problems. False five problems were manipulated to violate arithmetic rules (i.e., five-rule, parity-rule, or both parity and five-rules) or to violate no rules. Each arithmetic problem was preceded by an emotionally negative or neutral picture that participants had to compare with a picture following each problem. We replicated previously found effects of problem type (i.e., five/non-five problems) and effects of rule violation (i.e., parity-rule, five-rule, or both-rule violation) under neutral emotions (e.g., Hinault, Dufau, et al., 2015; Hinault, Tiberghien, et al., 2015; Hinault & Lemaire 2017; Lemaire & Siegler, 1995). We also replicated decreased performance under negative emotions relative to neutral emotions (e.g., Fabre et al., 2022; Fabre & Lemaire, 2019; Kleinsorge, 2009; Lallement & Lemaire, 2021; Liu et al., 2021; Schimmack, 2005). Most originally, we found that deleterious effects of negative emotions on arithmetic problems vary with problem types and with participants' age. More specifically, deleterious effects of emotions were found (a) in young adults while solving true and false non-five problems as well as false five problems and (b) in older adults while solving true five problems only. These findings have important implications for furthering our understanding of how emotions influence arithmetic performance and of how effects of emotions on arithmetic performance change with age during adulthood.

Effects of emotions during arithmetic problem-solving tasks

We found poorer performance under negative emotion condition than under neutral emotion condition, replicating prior findings in arithmetic (Fabre & Lemaire, 2019; Kleinsorge, 2009; Lallement & Lemaire, 2021; Liu et al., 2021; Schimmack, 2005). Previous studies found that emotions hindered young participants' performance while verifying true, non-five problems. Deleterious effects of negative emotions on math performance have previously been explained by assuming that negative information more readily capture participants' attention than other type of information (Verbruggen & De Houwer, 2007; Yiend et al., 2013) and distract attentional resources, leaving fewer resources for the target problem-verification task (e.g., Fabre & Lemaire, 2019; Lallement & Lemaire, 2021; Verbruggen & De Houwer, 2007). This is most likely what happened in the present study while participants verified true, non-five problems. However, here, emotions did not impair young participants' performance while verifying easier true, five problems. Better performance on five than on non-five problems has been found in previous studies (e.g., Campbell & Oliphant, 1992), as five problems are easier than non-five problems. Both five and non-five true problems are assumed to be solved by exhaustive verification strategies. Such strategies involve encoding the problem (operands and proposed answers), searching the correct answer (via retrieval or calculation), comparing correct and proposed answers, making true/false decision, and providing response. Finding the correct solution for five problems is easier and faster, leading participants to better performance on five than on non-five problems. The present lack of deleterious effects on young participants' performance for five problems suggest that emotions hinder arithmetic performance on harder problems and not on some easier problems. Five problems are easier and require fewer resources, such that even if emotions captured some of the available resources, young participants had enough resources left free to efficiently verify those true, five problems. At a more general level, this suggests that deleterious effects of emotions on arithmetic performance occur when it is harder for participants to find the correct answer. When the correct answer is more easily found, negative emotions may have no deleterious effects.

Most originally, the present findings also revealed that arithmetic performance was influenced by emotions for some false, five problems but not for other false, five problems. Surprisingly, young adults increased their speed under negative emotions while rejecting false five problems violating no arithmetic rules. Such findings were unexpected as previous studies found that, like for true non-five problems here, participants tend to slow down under negative emotions. Note that emotion-related speed up has already been found in numerical cognition studies (Fabre et al., 2022; Hamamouche et al., 2017) in which young participants were faster to estimate numerosity of collections of elements following emotionally negative pictures. It was interpreted as resulting from heightened attention toward the target estimation task and from participants' intentionally trying to quickly disengage from negative emotions triggered by emotionally negative pictures. Here, it is possible that such mechanisms were involved and facilitated participants' performance while processing false, five, no-rule violation problems. Why such speed-up occurred for false, five, no-rule violation problems and not for other problems is still unknown. But it should be replicated in future studies and further scrutinized.

Interestingly, we also found no change in verification times when young adults verified false, five problems violating the parity or the five rules under the negative emotion condition compared to the neutral condition. Probably, because when they solve these rule-violation problems, participants use fast, rule-violation checking strategies, these fast rule-violation checking strategies do not require much resources (or much less resources than exhaustive verification strategies used to verify true five or non-five problems). As a consequence, even if emotional processing captures attentional resources, enough resources are left available to use and execute these rule-violation checking strategies.

Note that the lack of effects of negative emotions on the use of parity-rule and five-rule violation checking strategies does not mean that negative emotions do not influence the use of any rule-violation checking strategies. Indeed, when participants verified problems that violated both the parity and five rules, they were slower under negative emotion condition. This likely resulted from participants' using the both-rule violation checking strategies less often and the exhaustive verification strategies more often under negative emotions while verifying these two-rules violation problems. They did check whether arithmetic rules were violated, as they were faster on those two-rules violation problems than on no-rule violation problems. However, they probably did not do so as systematically, efficiently, and as often under negative emotion than under neutral condition.

Undetermined is how emotions could influence the use of some fast, rule-violation checking strategies (like both-rule violation checking strategy) and have no effects on the use of other fast rule-violation checking strategies (like parity-rule and five-rule violation checking strategies). Future studies will have to further examine this issue. Speculatively, at this stage, it is possible to imagine that compared to when problems violate only one rule, we are faster to detect the violation of two rules (Hinault, Dufau, et al., 2015; Hinault & Lemaire, 2016) but we need more cognitive resources to execute the fast rule-violation checking strategy. With fewer resources available under negative emotion condition, it is possible that detection of both rule violations was less systematic and/or less efficient than detection of one rule violations.

In sum, the present findings showed that emotions impaired participants' performance when they used exhaustive verification strategies on harder problems (i.e., true non-five problems and false, five, no-rule violation problems) but not when they used this strategy on easier problems (i.e., true five problems). Also, young adults' performance was influenced by negative emotions when they used arithmetic-rule violation checking strategies if problems violated two rules but not if problems violated one rule. At a very general level, the present findings suggest that influence of emotions on participants' arithmetic problems may depend on the type of strategies they are using to solve problems. Future studies may test this possibility directly by assessing on each problem which strategy participants use and how efficient they are at executing the selected strategies under emotionally neutral and negative conditions.

Age-related differences in effects of emotions during arithmetic problem-solving tasks

One of the most original findings in our study is that effects of emotions differed in young and older adults, when participants solved both true and false problems, as well as when they solved five and non-five problems. Such age differences cannot be explained by older adults' not processing emotional pictures, as effects of emotions occurred in older adults while verifying false, five problems, and as our picture recognition task forced them to process emotional pictures. To understand these age-related differences, it is important to examine how they varied with problem types.

Two intriguing sets of findings regarding age-related differences in effects of emotions came out in this study when we consider these differences for each type of problem. First, whereas emotions impaired young adults' performance while solving the most difficult, true non-five problems, deleterious effects of emotions occurred in older adults when they solved the easier, true five problems. This is surprising because if emotional processing captures attention resources, given that older adults have fewer resources available than young adults, they should be more impaired by emotions while solving the hardest, non-five problems than the easier, five problems, as the former require more resources. In different cognitive tasks, deleterious effects of negative emotions in older adults have been found larger on more difficult tasks or conditions (Knight et al., 2007; Mikels et al., 2010; Spaniol et al., 2008). Here, in arithmetic, this is not what happened. Effects of emotions were observed only while solving the easier five problems. Note however, that in some studies stronger effects of emotions have also been found on older adults' performance when the task is easier (e.g., Kensinger, 2008). One possible explanation can be derived from empirical and theoretical work on selective attention (Desimone & Duncan, 1995). Following this line of work, performance on a target task is less influenced by interfering information when participants are fully engaged in this task than when participants are less engaged. Because non-five problems are harder than five problems, it is possible that older adults were more fully engaged while solving these harder problems. This led them to focus more on the target task and less on the emotional processing. In turn, they were less influenced by negative emotions when they solved harder, non-five problems. Note that fuller engagement in a target cognitive task can be viewed as an emotional regulation strategy (i.e., attention redeployment) that older adults are known to use in some conditions (e.g., Sheppes, 2014) like here when they had to solve harder, non-five problems. Of course, the possibility that older adults regulated negative emotions on harder non-five problems more than on easier, five problems via fuller engagement should be further examined in future research.

The second set of intriguing but interesting findings concerns age-related differences in effects of emotions when participants solved false, five problems. Whereas emotions influenced young adults' performance when problems violated no-rule and both-rules, older adults' performance did not change under negative emotions for false five problems, whether these problems violated arithmetic rules or violated no rules.

The lack of effects of emotions in older adults on false, five problems could be explained by the robust age-related positivity effect (Mather, 2012; Mather & Carstensen, 2005; Reed et al., 2014; Reed & Carstensen, 2012). Age-related positivity effects are characterized by age-related changes in how negative and positive emotions influence cognitive performance. In a wide variety of cognitive domains, older adults have been found to be either more influenced by emotionally positive information or less influenced by emotionally negative information compared to young adults (see Lemaire, 2022, for an overview). Here, on these easiest, five, false problems, that most of which could be solved via fast, rule-violation checking strategies, older adults were less influenced than young adults, as they may have been able to better regulate potential interference from negative emotions. Their relatively high level of arithmetic fluency may have left enough resources available while solving these easier problems to execute emotional regulation strategies (e.g., quick disengagement of processing emotional pictures and re-engagement in the target arithmetic problem verification task). Interestingly, this suggests that the deployment of such emotion regulation strategies in young adults or in older adults while solving true, five problems could lead participants to be unaffected by negative emotions during arithmetic problem solving, a prediction that remains to be tested.

One important limitation of this study is that older adults' greater speed in the arithmetic problem verification task than young adults. This pattern of results suggest that the young adults' increased latencies may reflect lower arithmetic skills. Indeed, when we re-run the same analyses with arithmetic skills as covariates, we found a main effect of the covariate and an interaction between the rule violation, the emotion, and the covariate. Note that we have considered verification latencies on true non-five problems under neutral emotion as arithmetic skills indicator, consequently, these latencies were used as covariates in the present analyze. These results highlight a new factor, as arithmetic skills, to take in consideration to explain differences in emotion effect between young and older adults. Effectively, unknow is if the difference of influence between young and older adults may be explain by a real difference between both groups or a difference in arithmetic skills in young and older adults. Future studies need to take into account the arithmetic skills to control this parameter using for example the addition and subtraction-multiplication subtests of the French Kit (French et al., 1963) and by asking participants if they manipulate arithmetic data in their daily lives. Also, another important limitation of the current study concerns how negative emotions influenced young and older adults' arithmetic performance. Above and beyond general mechanisms of attentional capture, we proposed that effects of emotions in young and older adults differed for each problem type via each problem type being solved by different arithmetic problem-solving strategies. Strategy variability is a hallmark of arithmetic (Siegler, 2007). Future studies may gain further insights regarding how emotions affect arithmetic performance and how effects of negative emotions on arithmetic performance change during adulthood by assessing strategies on each problem and by comparing strategy use and strategy execution under emotionally negative and neutral conditions. This would also provide more direct evidence for a strategy account of effects of negative emotions on arithmetic performance and for age-related differences in these effects.

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Authors' contributions All authors generated the idea for the study. Paola Melani coded the data and analyzed the data. All authors provided feedback on the analyses. Paola Melani wrote the first draft of the manuscript; all authors critically edited it and approved the final submitted version of the manuscript.

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Data accessibility Data files of this study can be found at https://osf.io/gfsqy/?view_only=d506158931e347d1add8a95ad4997048.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethic approval This study was performed in line with the principles of the Declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

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