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Aging, Emotion, and Cognition: The Role of Strategies

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In three experiments, I examined the role of emotions in arithmetic and investigated how this role changes with aging. I adopted a strategy approach and examined strategic aspects of participants' performance under emotionally neutral and negative conditions. The data showed that negative emotions led participants to (a) use fewer strategies and change how often they used each available strategy (Experiment 1), (b) select the better strategy on each problem less often while solving both easier and harder problems (Experiment 2), and (c) obtain poorer performance (Experiments 1 and 3), even when strategy repertoire, distribution, and selection were controlled. Regarding age-related differences, I found that negative emotions (a) influenced efficiency of strategy execution less strongly in older adults than in young adults, (b) affected young adults' strategy repertoire but not older adults', (c) changed strategy distributions more strongly in young than in older adults, and (d) influenced strategy selection to the same extent in both age groups. These effects of emotions on strategy repertoire, distribution, execution, and selection, and age-related differences in these effects have important implications for explaining how emotions influence the mechanisms underlying task performance and to improve our understanding of how influence of emotions on cognition changes during aging.

Public Significance Statement

This study shows that negative emotions can have profound effects on how participants approach cognitive tasks by changing the strategies participants use. The study also shows that both similar and different mechanisms are responsible for deleterious effects of negative emotions in older and young adults.

Keywords: emotion, cognition, aging, strategies, arithmetic

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Over 30 years of research on cognitive aging revealed that our cognitive capacities decrease with age (see Craik & Salthouse, 2015; Thomas & Gutchess, 2020 for overviews). However, age-related changes in cognitive performance are modulated by several parameters, like participant, task, stimulus, and situation features. Emotion is one characteristic that is known to influence cognitive performance and cognitive aging. Recent findings on how emotion and cognition interact and on how such interaction changes during aging have had a profound impact on what we know on (and our representations of) cognitive aging. Indeed, previous findings revealed that (a) negative emotions do not influence young and older adults' cognitive performance to the same extent and (b) age-related differences in cognitive performance are modulated by emotions. For example, in a wide variety of cognitive tasks, negative emotions impair older adults' performance less than young adults' and age-related differences in cognitive performance tend to decrease (and sometimes disappear or reverse) when participants are tested under emotion conditions (Dolcos et al., 2014; Lemaire, 2022a). However, which mechanisms are responsible for effects of emotions on cognitive performance and for how these effects change during aging are unclear. The goal of the present experiments was to further understand these mechanisms. To achieve this end, I adopted a strategy perspective that investigates cognition and cognitive aging in terms of which strategies are used and how often each strategy is used, as well as how participants select and execute cognitive strategies (Lemaire, 2010, 2016). Before presenting the logic of the present study, I briefly review previous findings on the effects of emotions on cognitive performance, and age-related changes therein.

Effects of Emotions on Cognitive Performance

Research investigating the effects and underlying mechanisms of emotions on cognitive functioning aims at determining if, when, and how emotions influence cognitive performance. Previous works in

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Patrick Lemaire served as lead for conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing–original draft, and writing–review and editing.

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young adults found that emotions lead to sometimes improved and sometimes decreased performance across a wide variety of domains (De Houwer & Hermans, 2010; Lemaire, 2022a; Robinson et al., 2013). For example, in reasoning, participants obtain poorer performance when they reason on emotional content (e.g., Blanchette & Richards, 2004; Eliades et al., 2013), but better performance when emotional content of reasoning problems is congruent with individuals' past emotional experiences (e.g., Blanchette & Campbell, 2012; Caparos & Blanchette, 2016). As another example, in episodic memory, several studies reported that participants recalled emotional words (e.g., rape) better than neutral words (e.g., table). This outcome was found both in incidental and intentional memory tasks, recall and recognition tasks, and when stimuli were isolated (or pairs of) words as well as with texts, images, and scenes (e.g., Kensinger & Kark, 2018). Note that emotions do not always have facilitative effects on memory. In some emotional contexts (e.g., stress), memory performance decreases (Kuhlmann et al., 2005; Miranda & Kihlstrom, 2005). In attention, the brief presentation of emotional images disrupts performance in stop-signal tasks (e.g., Kalanthroff et al., 2013; Nakakoga et al., 2021). In judgment, emotions tend to bias participants' estimates of probabilities of different events (e.g., Constans & Mathews, 1993; Johnson & Tversky, 1983; Mayer et al., 1992; Schwarz & Clore, 1983; Small & Lerner, 2008). Thus, participants tend to overestimate likelihood of positive events when positive emotions are experimentally induced, and of negative events when negative emotions are experimentally activated. Finally, we tend to make decisions aimed at decreasing risks under positive emotions (e.g., Cheung & Mikels, 2011; Isen & Geva, 1987; Isen & Patrick, 1983; Miu & Crişan, 2011), and we make poorer decisions following more superficial information processing under negative emotions (e.g., Lighthall et al., 2009; Moretti & di Pellegrino, 2010; Otto et al., 2013; Porcelli & Delgado, 2009; Raghunathan & Pham, 1999; Schwabe & Wolf, 2009).

Most effects of emotions on cognition are accounted for in terms of general processing mechanisms (e.g., Okon-Singer et al., 2015; Verbruggen & De Houwer, 2007). For example, researchers often assume that emotional cues grab exogenous attention and modulate endogenous attention, that emotional distractors disrupt cognitive control, that emotions strengthen some cognitive processes while weakening others, or that emotions use up processing resources within working memory.

However, one of the limitations of such explanations is that they more or less implicitly assume that participants accomplish tasks with the same cognitive mechanisms under emotional and neutral states. What would change is the amount of attention that is devoted to these mechanisms and, as a consequence, how efficient these mechanisms are under emotion conditions. Unknown is whether, above and beyond effects of general processing resources (e.g., attention, cognitive control, working memory), participants use the same versus different sets of mechanisms when accomplishing cognitive tasks under emotional versus neutral states. Also, if the same cognitive mechanisms are used to accomplish a given cognitive task under emotional and neutral states, we do not know if these mechanisms are executed with the same levels of efficacy.

Although effects of emotions on cognitive performance are well documented in a wide variety of cognitive domains, the underlying mechanisms, or how they affect people's approaches to cognitive tasks, are still poorly understood. Determining whether emotions influence which cognitive mechanisms are used and how they are executed to accomplish cognitive tasks is crucial if we are to provide mechanistic accounts of how emotions influence cognition and how this influence changes during adulthood. One of the goals of the present project is to further our understanding of mechanisms underlying effects of emotion on cognition and age-related changes in these mechanisms.

Age-Related Changes in How Emotions Influence Cognitive Performance

Previous works comparing effects of emotions on cognition in young and older adults revealed that some of the emotional effects on cognition increase with age during adulthood, while others decrease, and that emotions often modulate age-related differences in cognitive performance (Dolcos et al., 2014; Lemaire, 2022a; Reed & Carstensen, 2012; see Lemaire, 2022a for an overview). For example, older adults have poorer performance than young adults when they memorize emotionally neutral images, faces, or words. However, differences between young and older adults' performance are dramatically decreased, and sometimes absent, when participants memorize emotionally positive images (e.g., Chainay et al., 2014; Charles et al., 2013). As another example, Mikels et al. (2005; Plancher et al., 2019) found that working-memory maintenance of emotional material was not impaired in older adults, and that older adults exhibited better performance on positive relative to negative emotion trials (and the reverse in young adults). Similarly, older adults solve emotionally salient and interpersonal problems in more effective ways than young adults (e.g., Blanchard-Fields, 2007).

In addition to showing that emotions modulate age-related differences in cognitive performance, previous works suggest that emotions change age-related differences in attentional biases, such that older adults tend to focus more on positive information (an effect referred to as an age-based positivity effect; Mather & Carstensen, 2005). Thus, in decision making, for example, older adults pay more attention to positive than to negative attributes when choosing among doctors and hospitals, cars, and consumer products (e.g., Lockenhoff & Carstensen, 2008).

Although how emotions change age-related differences in cognitive performance has been well documented in many cognitive domains, previous works are limited in two respects, empirical and theoretical. Empirically, effects of emotions on young and older adults' cognitive performance have been much less investigated in some domains (e.g., spatial, numerical cognition) than in others (e.g., attention, memory, reasoning). Theoretically, unclear are the mechanisms responsible for how effects of emotions on cognition change during adulthood, so that we ignore whether differences in effects of emotion on young and older adults' cognitive performance result from the same or different developmental mechanisms.

When we want to compare effects of emotions on cognition in young and older adults, it might be important to do it in cognitive domains where age-related differences are inexistent or smaller under emotionally neutral conditions, for several reasons. First, it enables us to characterize effects of emotions in both young and older adults independently of participants' baseline performance. Second, we can compare magnitudes and direction of effects of emotions across age groups in domains where age-related differences in baseline performance exist (e.g., memory, attention) and in domains where they do not exist or are much smaller (e.g., arithmetic, language). This would enable us to determine the contributions of age differences in baseline performance to age differences in effects of emotions on cognitive performance. Also, it would contribute to determine whether older adults' high proficiency in one domain gives them resources to resist interference from emotions. Finally, it would help to better estimate how emotions contribute to or decrease age-related differences in cognitive performance. In this context, here, we examined effects of emotions in arithmetic, a domain where age-related differences are either nonexistent or much smaller than in many other domains (see Duverne & Lemaire, 2005; Uittenhove & Lemaire, 2018; Uittenhove et al., 2015, for reviews).

Effects of Emotions in Arithmetic

In arithmetic, performance is known to vary with a number of factors characterizing problems, participants, and situations. Previous studies found that participants who feel anxiety about mathematics obtain poorer performance while solving arithmetic problems (see Dowker et al., 2016; Mammarella et al., 2019 for reviews), as evidenced by negative correlations ranging from −.28 to −.48 between arithmetic performance and mathematics anxiety.

Also, several studies manipulated participants' emotional states and found that negative emotions have deleterious effects on participants' performance (Fabre & Lemaire, 2019; Fabre et al., 2023; Framorando & Gendolla, 2018, 2019; Kleinsorge, 2007, 2009; Lallement & Lemaire, 2021; Lemaire, 2022b; Lemaire & Brun, 2018; T. Liu et al., 2011; Schimmack & Derryberry, 2005). For example, Lallement and Lemaire (2021) asked participants to verify simple arithmetic problems (e.g., $8 + 4 = 12$. True? False?) or solve complex problems (e.g., closest product from 32×46 is 1,200 or 2,000?). Each problem was shown superimposed on emotionally neutral or negative images. Participants were slower under negative emotions, and even more so for harder than for easier problems. Following general accounts of how emotions influence cognitive performance, participants' longer latencies in arithmetic under negative emotion condition relative to neutral condition were explained as attentional interference effects. Because participants' attention was captured by negative emotion processing, it was detracted away from the arithmetic task, and participants had to disengage from processing emotional pictures and to switch to processing arithmetic problems.

Effects of Emotions on Cognition: A Strategy Perspective

A promising perspective on effects of emotions on cognition is the strategy perspective. This strategy perspective is based on previous findings that people use several strategies to accomplish cognitive tasks (Siegler, 2007), and that condition-related and age-related differences in participants' performance are systematically associated with strategic variations in a wide variety of cognitive domains (Lemaire, 2016). A strategy is "a procedure or set of procedures for achieving a higher-level goal or task" (Lemaire & Reder, 1999, p. 365). According to the strategy perspective, effects of emotions would occur via impairing participant's ability to use multiple strategies, to select the best strategy on each item, to use more efficient strategies most often, and/or to execute strategies efficiently. Following previous findings in arithmetic regarding correlations between math anxiety and strategy use (Si et al., 2014, 2016) and on affective priming effects on strategy use (Zhu et al., 2021), a strategy perspective might be fruitful to understand responsible mechanisms for deleterious effects of negative emotions on participants' performance. Given that investigating strategic aspects of cognitive performance is determining the mechanisms via which participants accomplish cognitive tasks, adopting a strategy perspective is fruitful when we ask if emotions change the mechanisms via which participants accomplish a cognitive task, and how this changes with age during adulthood. Indeed, it enables us to determine, for example, whether young and older participants accomplish a task with the same strategies under emotionally negative and neutral conditions, and if they do, whether they execute strategies with different levels of efficacy, and/or whether they use a different set or a different number of strategies. Young and older adults may differ in whether emotions influence strategy repertoire, strategy selection, and strategy execution. In other words, the present work tested the possibility that effects of emotions on cognition might be mediated by strategic variations and that there may be age-related differences during adulthood in such mediation.

One study found indirect evidence that negative emotions may impair strategic aspects of participants' performance. Following previous works on emotions and arithmetic (Kleinsorge, 2007, 2009; Schimmack & Derryberry, 2005), Fabre and Lemaire (2019) (see also Melani et al., 2023) asked young adults to verify arithmetic problems (e.g., $4 \times 32 = 128$. True? False?). Immediately before each problem, participants saw a negative or a neutral image for 1,500 ms. Fabre and Lemaire found smaller parity-violation effects after negative pictures than after neutral pictures. In parity-violation effects, participants are faster to reject false problems that violate parity rule (i.e., "to be true, a product must be even, if either of its multipliers is even; otherwise, it must be odd," Lemaire & Fayol, 1995, p. 35, like in $6 \times 12 = 71$) than on problems that respect the parity rule (e.g., $6 \times 12 = 74$). Parity effects are usually accounted for by assuming that participants use two different strategies. Participants quickly check whether the parity rule is violated or respected on parity-rule violation problems and use an exhaustive calculation strategy on problems that respect parity rule. The parity-rule violation strategy is faster than an exhaustive calculation strategy because participants quickly detect that the parity rule is violated and do not calculate the correct answer (e.g., Lemaire & Fayol, 1995; Lemaire & Reder, 1999; Lochy et al., 2000). Fabre and Lemaire proposed that smaller parity effects under negative emotions might result from participants using the calculation strategy both when problems violated and respected the parity rule. This suggests that negative emotions impair flexible strategy use, lead participants to use a single strategy on all problems, and/or execute strategies more poorly. One of the limitations of this study was that the performance data provide only indirect evidence for emotions to influence cognitive performance via strategy differences. Another limitation is that Fabre and Lemaire tested only young participants, while other data (Lallement & Lemaire, 2021) showed that negative emotions influence both young and older adults' arithmetic performance. Thus, the present experiments tested the role of strategies directly by examining which and how many strategies participants use under neutral and negative emotions, how often they select the better strategy on each problem, and how fast and accurate they are while executing available strategies. Finding evidence that emotions influence cognitive performance via strategic variations would suggest that effects of emotions on cognition are mediated by the strategies that people use, select, and execute.

Overview of the Present Study

We conducted three experiments to test the strategy hypothesis of effects of emotions on cognition and age-related differences in these effects. According to the strategy hypothesis, participants may use fewer strategies to accomplish a cognitive task, use different sets of strategies, select, use available strategies unequally often, and/or execute strategies on each problem differently, under neutral and negative emotions. In addition to differences in participants' performance between negative and neutral emotions, we tested effects of emotions on young and older adults' strategy repertoire and distribution (Experiment 1), strategy selection (Experiment 2), and strategy execution (Experiment 3).

Following previous studies in arithmetic (Fabre & Lemaire, 2019; Kleinsorge, 2007, 2009; Lallement & Lemaire, 2021; D. Liu et al., 2021; Schimmack & Derryberry, 2005), we used a within-trial emotion induction procedure to test young and older adults. Each arithmetic problem was preceded by an emotionally negative or neutral pictures and was then presented superimposed on these pictures.

Young and older individuals had to accomplish arithmetic problem-solving tasks (i.e., two-digit addition problem-solving and computational estimation tasks) following previous works showing that these arithmetic problem-solving tasks yield external behavioral evidence of strategies. Such evidence is not only independent of participants' performance but also increases our confidence in how participants accomplish cognitive tasks and in the fact that participants use different strategies and/or execute them differently under different conditions. Also, previous works showed that it is possible to instruct participants which strategy to use on each problem and to control that they comply with strategy instructions (e.g., Dowker et al., 2016; LeFevre et al., 1993; Lemaire & Leclère, 2014; Lemaire et al., 2004).

Experiment 1: Aging, Emotions, and Strategy Repertoire

Experiment 1 aimed at determining whether negative emotions influence strategy repertoire and whether this influence changes with participants' age during adulthood. We asked young and older adults to solve two-digit addition problems. This task was tested as previous studies revealed that participants use a wide variety of strategies to find sums of two-digit addition problems (e.g., Beishuizen, 1993; Beishuizen et al., 1997; Blöte et al., 2001; Fuson et al., 1997; Geary et al., 2004; Lemaire & Brun, 2018; Lemaire & Callies, 2009; Lucangeli et al., 2003). Detailed analyses of strategies used on each problem revealed that both young and older participants used nine strategies in this task (e.g., Hodzik & Lemaire, 2011; Lemaire & Arnaud, 2007). Here, we assessed which strategy was used as well as participants' performance on each problem and compared young and older adults' strategy use and performance in neutral and negative emotion conditions.

Above and beyond effects of emotions on arithmetic performance, the hypothesis that negative emotions change strategy repertoire predicts that participants use fewer strategies in the negative than in the neutral condition. This would occur if emotions capture attentional resources and fewer resources are left free to maintain activated in working memory a larger set of strategies to choose among on each problem.

Regarding age-related differences in how emotions change strategy repertoire, we expected young adults' strategy repertoire to be more influenced by negative emotions than older adults'. This would be seen if differences in mean number of strategies between negative and neutral conditions are larger in young adults than in older adults. As discussed earlier, such smaller influence of negative emotions in older adults would be consistent with previous findings of age-related positivity effects showing that older adults' cognitive performance is more affected by positive emotions and less affected by negative emotions than young adults'. Alternatively, if the set of strategies used by both age groups is similarly influenced by negative emotions, decreased number of strategies used by individuals under negative emotion condition should be the same in both age groups.

Method

Participants

Twenty-nine young and 28 older adults participated in Experiment 1. In all three experiments, older adults were volunteers from distinct French metropolitan areas, and young adults were undergraduate students at Aix-Marseille University who received course credit for their participation. Demographic information (see Table 1) for each participant was collected at the beginning of experiments with open-ended questions (e.g., What is your age? What is your gender?). The target sample size was determined using an a priori power analysis (G*Power; Faul et al., 2007). In the first study on age-related differences in strategy repertoire used to solve similar two-digit addition problems, Lemaire and Arnaud (2007), Lemaire and Brun (2018), and Lemaire and Lecacheur (2011) found an effect size of $\eta_p^2 = .22$. Using a $\eta_p^2 = .22$, our study design of one between-participants factor (age) and two within-participants factors (emotion, problem size) could achieve 90% power with 40 participants. In order to exceed this criterion, we recruited 57 participants. In all the experiments, participants gave their written informed consent. These experiments received approval from the National Ethics Committee in France (Ref.: SI CNRIPH 20.04.02.47414).

In Experiments 1–3 reported here, before the target arithmetic tasks, all older adults accomplished the mini-mental state examination (MMSE) to globally assess cognitive impairment in older adults (Folstein et al., 1975). No older adults were excluded because they all had scores larger than the usual cutoff score of 27 (out of 30).

Next, participants completed the French Kit (a pencil-and-paper arithmetic fluency test; French et al., 1963). In this test, participants were asked to solve as many problems as possible within the 2-min limited duration for each subset of basic addition, subtraction, and multiplication problems. Total number of correct answers yield an arithmetic fluency score. As is often found, older adults' arithmetic fluency scores were larger than young adults'.

Then, individuals' verbal fluency was assessed with the Mill–Hill Vocabulary Scale (MHVS; Deltour, 1993; Raven et al., 1998). In MHVS, participants see 33 items (including one target word and six proposed words). Participants had to indicate which of the proposed words had the same meaning as the target word. As is often found, the number of correct items was smaller in young than in older adults.

Arithmetic Problems

Each participant solved the same set of 96 complex addition problems (see the list of problems in Table S1 in the online supplemental materials). These problems were used in our previous studies (Hodzik & Lemaire, 2011; Lemaire & Arnaud, 2007; Lemaire & Brun, 2018). They were made of 2 two-digit numbers (e.g., 32 + 56). Two types of problems were tested, smaller and larger problems, depending on the size of correct sums and on whether or not they

Table 1
Participants' Characteristics in Experiments 1–3

Characteristics	Young adults	Older adults	*F*
Experiment 1: strategy repertoire			
N (female/male/binary)	29/16/0	28/13/0	—
Age (*SD*)	23 (4.10)	70 (6.81)	1,008.126
Range	18–32	61–86	—
Arithmetic fluency (*SD*)	32 (15.11)	55 (20.22)	22.931
Vocabulary (*SD*)	19 (7.05)	25 (6.03)	14.514
Mental state	—	29 (0.99)	—
Experiment 2: strategy selection			
N (female/male/binary)	29/12/0	29/18/0	—
Age (*SD*)	22 (3.13)	75 (7.45)	1,248.726
Range	18–30	64–95	—
Arithmetic fluency (*SD*)	40 (12.55)	56 (21.80)	12.038
Vocabulary (*SD*)	21 (3.49)	24 (4.54)	9.242
Mental state	—	29 (1.07)	—
Experiment 3: strategy execution			
N (female/male/binary)	29/16/0	29/17/0	—
Age (*SD*)	21 (2.85)	72 (6.98)	1,322.410
Range	18–31	65–89	—
Arithmetic fluency (*SD*)	33 (13.10)	51 (19.13)	16.037
Vocabulary (*SD*)	20 (3.90)	24 (4.69)	11.431
Mental state	—	29 (0.77)	—

Note. Vocabulary was assessed with the Mill–Hill Vocabulary Scale (Deltour, 1993; Raven et al., 1998). Mental state was assessed with the Mini-Mental State Examination (Folstein et al., 1975). Arithmetic fluency was assessed with the French Kit (French et al., 1963).

involve a carry on decades. Half the problems were "smaller problems." Their correct sums were smaller than 100, and they involved no carry (e.g., 13 + 64). The other problems were "larger problems." Their correct sums were larger than 100, and they involved carry on decades (e.g., 48 + 67).

The selection of problems was further constrained by previous findings in arithmetic (Cohen Kadosh & Dowker, 2015; Gilmore et al., 2018; Knops, 2020), as indicated in the note of Table S1 in the online supplemental materials.

Stimuli for Emotional Pictures

Ninety-six pictures were selected from the International Affective Picture System (IAPS, Bradley & Lang, 2007; Lang et al., 2008). Half the pictures depicted negative events (e.g., a snake) and half neutral events (e.g., a chair). Negative emotions included a variety of emotions (e.g., fear, disgust, sadness). Emotional valence and arousal were matched across each problem type (see Table 2).

Procedure

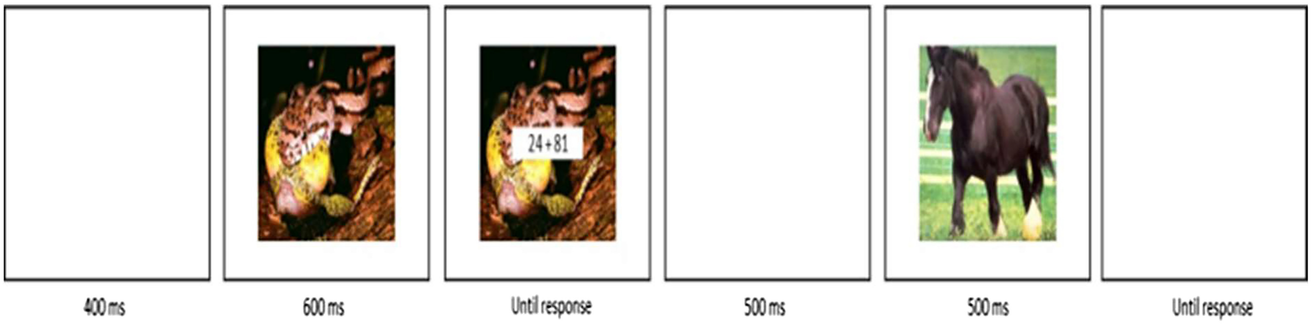
Participants were tested individually in one session which lasted approximately 45–60 min. First, they performed the paper-and-pencil tests (i.e., MMSE, arithmetic fluency, MHVS). Second, they accomplished the arithmetic problem-solving task.

In the arithmetic task, each trial started with a blank screen for 400 ms (see Figure 1) of a Dell Latitude 5590 15-inch computer screen. Then, participants saw a picture for 600 ms in the middle of the computer screen. They were told to remember this picture. Then, they saw a problem horizontally displayed (70-point Arial font) in the center of the picture. Participants had to find the sum of each problem. They were told to do this as quickly and accurately as possible and to calculate

Table 2
Emotional Valence (Mean, Range, and Standard Deviation) and Arousal Ratings for Smaller and Larger (Simple/Complex) Problems in Experiments 1–3

Problems	Neutral	Negative
Experiment 1: emotional valence		
Smaller	5.04 (4.53–5.49; 0.26)	1.98 (1.45–3.78; 0.51)
Larger	5.03 (4.63–5.50; 0.21)	1.87 (1.31–3.15; 0.45)
Experiment 1: arousal ratings		
Smaller	3.26 (1.76–5.71; 0.78)	6.36 (5.25–7.26; 0.59)
Larger	3.03 (1.72–4.14; 0.53)	6.50 (5.48–7.22; 0.49)
Experiments 2 and 3: emotional valence		
Simple	5.36 (5.24–5.52; 0.07)	1.77 (1.31–2.30; 0.27)
Complex	5.33 (5.22–5.48; 0.07)	1.95 (1.40–3.78; 0.59)
Experiments 2 and 3: arousal ratings		
Simple	3.53 (2.42–4.25; 0.55)	6.55 (5.62–7.26; 0.55)
Complex	3.72 (2.32–4.88; 0.66)	6.34 (5.53–7.22; 0.49)

Figure 1
Sequence of Events of an Example Trial



Note. On each trial, participants first saw a picture, then solved an addition problem, and then saw a picture. Participants had to say whether the two images were the same or different. From "International Affective Picture System (IAPS): Affective Ratings of Pictures and Instruction Manual," by P. J. Lang, M. M. Bradley, and B. N. Cuthbert, 2008, Technical Report A-8, University of Florida, Copyright 2008 by the University of Florida. Reprinted with permission. See the online article for the color version of this figure.

out loud. This enabled us to determine their strategies. Following numerous previous studies (e.g., Lemaire & Brun, 2016, 2018; Nicolas et al., 2021), solution latencies corresponded to the time elapse between the beginning of the problem display and ended with participants' response. The experiment was run on the Open Sesame 3.3.12 software. Following participants' response, problems disappeared and a blank screen appeared for 500 ms. Then, participants saw a picture for 500 ms. This second picture was the same as the first in half the trials, and different in the other trials. Participants had to indicate whether both pictures were the same or different. This picture judgment task enabled us to make sure that participants processed the emotional pictures. The experimenter wrote down participants' answer to the arithmetic problem, to the picture question, and coded the strategy used on each problem. Participants were 98% correct in the picture judgment task and were equally fast to provide their judgments on neutral and negative emotion pictures, 1,130 ms versus 1,125 ms, $F < 1.0$.

Half the problems were displayed with an emotionally negative picture and the other problems with an emotionally neutral picture. Problems were matched across emotion conditions on the number of smaller and larger problems, on mean sum, the number of problems with a carry on decade digits, and on the side of the larger operand. Problems were randomly presented to participants, with the constraint that no more than three successive trials involved the same emotional valence. Before the experimental arithmetic task, participants underwent a practice session. First, the nine available strategies were described in detailed and illustrated with two problems each. Then, participants practiced each strategy with five problems. Finally, they accomplished six practiced trials in the experimental task (i.e., they solved arithmetic problems displayed on three emotional and three neutral images and judged whether the images were the same or not). Following this practice session, participants saw two blocks of 48 trials each, with a brief pause in-between each block.

The nine available strategies were those found by Lemaire and Arnaud (2007), Hodzik and Lemaire (2011), and Lemaire and Brun (2018). These strategies are listed in Table 3.

Transparency and Openness

I reported how I determined sample sizes for all three experiments, all data exclusions, all manipulations, and all measures in the study, and I followed JARS (Kazak, 2018). The experiments' designs and their analyses were not preregistered.

Table 3
List of Available Strategies (and Example)

Strategy	Description	Example (13 + 64)
Rounding the first operand down	Participants rounded the first operand down to the closest smaller decade, added this rounded number to the other operand, and added this sum to the difference between first operand and this operand rounded to the closest smaller decade.	(10 + 64) + 3
Rounding the second operand down	Participant did the same as when using the rounding the first operand down but with the second operand.	(13 + 60) + 4
Rounding both operands down	Participants rounded both operands down to their closest decades, added these two rounded numbers, and added this sum to the differences between rounded operands and their closest smaller decades.	(10 + 60) + (3 + 4)
Columnar retrieval	Participants first added the units and then the decades.	(3 + 4) + (60 + 10)
Rounding the first operand up	Participants rounded the first operand up to the closest decade, added the rounded number to the second operand, and subtracted from this sum the difference between first operand and this operand rounded to its closest larger decade.	(20 + 64)−7
Rounding the second operand up	Participants did the same as when rounding the first operand up but with the second operand.	(13 + 70)−6
Rounding both operands up	Participants rounded both operands up to their closest decades, added these two rounded numbers, and subtracted from this sum differences between rounded operands and their closest decades.	(20 + 70)−13
Borrowing units	Participants borrowed units from one operand to round the other operand up or down to its closest decade and added these transformed operands.	17 + 60
Direct retrieval	Retrieving the sum directly from memory.	77

Results

Results are reported in two main parts. The first part examines age-related differences in how emotions influence participants' strategies and the second analyzes age-related differences in effects of emotions on participants' performance. All analyses reported in this article were rerun with arithmetic fluency scores at the paper-and-pencil, French Kit test entered as covariates. However, the same effects came out significant.

Age-Related Differences in Effects of Emotions on Strategy Use

Strategy Variability. Participants showed strategy variability in both the neutral and negative conditions. Indeed, examining the number of strategies used by individuals (Table 4) revealed that participants did not use a single strategy, except five young adults and five older adults. Twelve young and 19 older adults used between two and five strategies, and 12 young and four older adults used between six and nine strategies in the neutral emotion condition. In the negative emotion condition, six young and eight older adults used only one strategy, 15 young adults and 15 older adults used between two and five strategies, and eight young adults and five older adults used between six and nine strategies. Similarly, examining the number of participants using each strategy on each problem revealed that no problems were solved by one or two strategies in young and older adults. Fourteen problems were solved by four or five strategies, and 30 problems were solved by six or seven strategies in young adults (corresponding figures are 32 and 16 problems, respectively, in older adults) when solving problems under the neutral emotion condition. In the negative emotion condition, 13 problems were solved by three to five strategies, and 35 problems were solved by six to eight strategies in young adults (corresponding figures are 29 and 19 problems, respectively, in older adults). In other words, at the levels of both individuals and problems, variability in the number of strategies was found in both neutral and negative emotion conditions.

Strategy Repertoire. A 2 (age: young, older adults) × 2 (emotion: neutral, negative) analysis of variance (ANOVA) on mean number of strategies used by individuals, with age as the only between-participants factor, revealed a main effect of age, $F(1, 55) = 4.03$, $MSE = 10.54$, $\eta_p^2 = .07$, $p = .05$, as older adults tended to use fewer strategies than young adults (3.1 vs. 4.3). Moreover, the main effect of negative emotion, $F(1, 55) = 13.74$, $MSE = 0.39$, $\eta_p^2 = .20$, $p < .001$, was significant and interacted with age, $F(1, 55) = 9.58$, $MSE = 0.39$, $\eta_p^2 = .15$, $p = .003$. Only young adults decreased their strategy repertoire in the negative emotion condition. Indeed, young individuals used 4.7 and 3.9 strategies under neutral and negative emotion conditions, respectively, $F(1, 28) = 17.76$, $MSE = 9.12$, $\eta_p^2 = .39$, $p < .001$. Corresponding means in older adults were 3.2 and 3.1, $F < 1.0$.

Strategy Distribution. Emotions influenced how often young and older adults used available strategies (see Table 5). Mean percent use of the eight strategies that were used on more than 1% of problems by both age groups were analyzed with an ANOVA involving a 2 (age: young, older adults) × 2 (emotion: neutral, negative) × 8 (strategies: rounding the first or the second operand down, rounding both operands down, columnar retrieval, rounding the first or second operand up, borrowing units, and direct retrieval), with repeated measures on the last two factors. There were main effects of emotion, $F(1, 56) = 5.29$, $MSE = 0.542$, $\eta_p^2 = .09$, $p = .025$, and strategy, $F(7, 392) = 36.76$, $MSE = 31{,}172.06$, $\eta_p^2 = .401$, $p < .001$, which interacted with each other, $F(7, 392) = 3.99$, $MSE = 35.118$, $\eta_p^2 = .068$, $p < .001$, showing different strategy distributions in neutral and negative emotion conditions. This interaction resulted from some strategies being used equally often under neutral and negative emotion conditions and other strategies being used unequally often. More specifically, columnar retrieval ($t = -2.351$; $p = .020$) and rounding second operand up ($t = -2.1681$; $p = .031$) were used significantly less often under negative emotion than under neutral emotion conditions. Rounding first operand up ($t = 2.842$, $p = .005$) was used significantly more often in the negative emotion condition. And all the other strategies (rounding the second operand down, rounding both operands down, rounding both operands up, and borrowing units; ts < 1.473, ps $< .124$) were used equally often under neutral and negative emotion conditions.

The Age × Strategy interaction, $F(7, 392) = 4.55$, $MSE = 3{,}814.03$, $\eta_p^2 = .076$, $p < .001$, was significant, showing different strategy distributions in young and older adults. Young adults' most often used strategy was columnar retrieval (39.3%), followed by rounding both operands down (15.0%) and borrowing units (14.5%). Young adults used the other strategies on 4.8%–7.2% of problems. Older adults'

Table 4
Strategy Distributions in Each Age Group Under Neutral and Negative Conditions

Age	Emotion	Number of strategies: 1	2	3	4	5	6	7	8	9
		Participant-based analyses								
Young adults	Neutral	5	2	5	2	3	2	3	6	1
	Negative	6	3	4	3	5	3	5	0	0
Older adults	Neutral	5	10	5	2	2	1	1	1	1
	Negative	8	8	4	1	2	2	0	3	0
		Item-based analyses								
Young adults	Neutral	0	0	0	1	13	22	8	4	0
	Negative	0	0	0	1	12	23	8	4	0
Older adults	Neutral	0	0	0	6	26	16	0	0	0
	Negative	0	0	0	3	26	14	5	0	0

Note. Each entry refers to the number of individuals in the participant-based analyses (e.g., five young individuals used one strategy in the neutral condition) or to the number of problems in the item-based analyses (e.g., young participants used five strategies on 13 problems in the neutral condition).

Table 5
Percentages of Use of Strategies in Young and Older Adults Under the Neutral and Negative Emotion Conditions

Strategy	Young adults		Older adults	
	Neutral	Negative	Neutral	Negative
1. Rounding the first operand down	5.4	5.0	2.4	2.2
2. Rounding the second operand down	6.5	7.1	1.9	2.4
3. Rounding both operands down	14.7	15.2	4.4	3.9
4. Columnar retrieval	40.3	38.3*	66.2	66.0
5. Rounding the first operand up	5.3	7.7*	2.2	3.1
6. Rounding the second operand up	5.7	3.8*	3.3	2.2
7. Rounding both operands up	1.4	0.5	0.1	0.2
8. Borrowing units	13.9	15.1*	7.3	8.9*
9. Direct retrieval	7.0	7.4	12.2	11.2

* $p < .05$.

most often used strategy was columnar retrieval (66.1%), followed by direct retrieval (11.7%) and borrowing units (8.1%). Older adults used the other strategies on 2.2%–4.2% of problems. In other words, although both age groups used columnar retrieval most often, older adults used it more often than young adults, young adults used borrowing units more often than older adults, and older adults used direct retrieval more often than young adults. Finally, the Age × Emotion × Strategy was not significant, $F(7, 385) = 1.142$, $MSE = 10.056$, $\eta_p^2 = .02$, $p = .336$.

Age-Related Differences in Effects of Emotions on Performance

Mean latencies (in ms) for correctly solved problems and percentages of errors (Table 6) were analyzed with ANOVAs involving 2 (age: young, older) × 2 (problem size: smaller, larger) × 2 (emotion: neutral, negative) mixed designs, with age as the only between-participants factor. The following effects came out significant on solution latencies: age, $F(1, 55) = 4.91$, $MSE = 8.349 \times 10^7$, $\eta_p^2 = .082$, $p = .031$; problem size, $F(1, 55) = 63.11$, $MSE = 8.182 \times 10^7$, $\eta_p^2 = .534$, $p < .001$; emotion, $F(1, 55) = 54.69$, $MSE = 1.184 \times 10^7$, $\eta_p^2 = .499$, $p < .001$; and Age × Problem Size, $F(1, 55) = 7.38$, $MSE = 9.570 \times 10^6$, $\eta_p^2 = .118$, $p = .009$. Older participants were faster than young participants (5,999 ms vs. 7,210 ms). Also, participants were faster on smaller (6,005 ms) than on larger problems (7,204 ms), and in the neutral (6,377 ms) than in the negative emotion condition (6,833 ms). And effects of problem size were larger in young (1,609 ms) than in older adults (789 ms). Although effects of emotions tended to be larger on larger problems (575 ms) than on smaller problems (338 ms), the Problem Size × Emotion interaction was not significant, $F(1, 55) = 2.38$, $MSE = 6.521 \times 10^4$, $\eta_p^2 = .041$, $p = .129$. Similarly, although effects of emotions tended to be larger in young adults (480 ms) than in older adults (433 ms), the Age × Emotion interaction was not significant, $F < 1.0$. The only effect that came out significant on mean percent errors was the effect of problem size, as participants made more errors on larger than on smaller problems (11.5% vs. 7.5%), $F(1, 55) = 13.41$, $MSE = 874.768$, $\eta_p^2 = .196$, $p < .001$. No other main or interaction effects came out significant in latencies or error rates. In sum, both young and older adults were slower and less accurate while solving larger than smaller two-digit addition problems and were slower in the negative emotion than in the neutral emotion condition.

Discussion

The present data bring support to the hypothesis that emotions influence strategy repertoire, but only in young adults. Indeed, negative emotions had deleterious effects on young and older adults' performance as they led participants to solve two-digit addition problems more slowly. Deleterious effects of negative emotions on participants' performance were of comparable magnitudes on young and older adults' performance. However, only in young adults did we find that negative emotions led participants to use fewer strategies and to change how often they use several of the available strategies. In other words, negative emotions led young adults to change the way they accomplish the arithmetic problem-solving task. Most likely, under negative emotions, young adults had fewer resources left free to maintain activated a larger set of strategies in working memory. Surprisingly, older adults did not change the number and distribution of strategies under negative emotions. This does not mean that they were insensitive to negative emotions. Emotions led older adults to be slower but not to reduce their strategy repertoire.

It is possible that lack of emotion-related differences in the number of strategies used by older adults stem from floor effects: Older adults used fewer strategies than young adults in the neutral condition (4.7 vs. 3.2). To examine this possibility, I divided the group of older adults into two groups on the basis of the number of strategies used by individuals in the neutral condition: smaller- versus larger-strategy repertoire groups. The larger-strategy repertoire

Table 6
Young and Older Adults' Performance (Latencies and Percentages of Errors) in the Neutral and Emotion Conditions as a Function of Problem Size (Experiment 1)

Problem size	Young adults				Older adults			
	Neutral	Negative	Means	Differences	Neutral	Negative	Means	Differences
Latencies (in ms)								
Smaller	6,210	6,601	6,406	391	5,463	5,747	5,605	284
Larger	7,730	8,298	8,014	568	6,103	6,684	6,394	581
Means	6,970	7,450	7,210	480	5,783	6,216	5,999	433
Percentages of errors								
Smaller	8.1	9.2	8.6	1.1	6.4	6.5	6.5	0.1
Larger	13.9	12.1	13.0	1.9	10.6	9.2	9.9	1.4
Means	11.0	10.6	10.8	0.4	8.5	7.9	8.2	0.6

group included 13 participants who used three or more strategies in the neutral emotion condition. On average, individuals in the larger-strategy repertoire group used 4.8 and 4.7 strategies in the neutral and negative emotion condition, respectively ($F < 1.0$). Thus, even when effects of negative emotions are compared in groups of older individuals who used a larger number of strategies under neutral condition, older adults are still not influenced by negative emotions in their strategy repertoire. Older adults' poorer performance under negative emotion condition suggests that negative emotions led older to execute and/or select strategies more poorly. Experiments 2 and 3 aimed at testing the role of negative emotions on young and older adults' strategy selection and strategy execution.

Experiment 2: Aging, Emotions, and Strategy Selection

Experiment 2 aimed at determining whether negative emotions influence strategy selection and whether this influence changes with participants' age during adulthood. Young and older adults accomplished computational estimation tasks with two-digit multiplication problems, instead of a two-digit addition problem-solving task. In computational estimation tasks, participants have to find approximate products to two-digit multiplication problems (e.g., 38 × 64), without calculating the correct products. This task was used because it is easy to unambiguously know whether participants use the better strategy on each problem. For example, to find the best estimate to 54 × 37, the rounding-down strategy (i.e., rounding both operands down to their nearest decades, like doing 50 × 30 = 1,500) is a better strategy than the rounding-up strategy (i.e., rounding both operands up to their nearest decades, like doing 60 × 40 = 2,400). Here, we assessed whether participants select the better strategy in addition to their performance on each problem and compared young and older adults' better strategy selection and performance in neutral and negative emotion conditions.

Above and beyond effects of emotions on computational estimation performance, the hypothesis that negative emotions change strategy selection predicts that participants use the better strategy on each problem less often in the negative emotion than in the neutral emotion condition. This would occur if emotions capture attentional resources and fewer resources are left free to analyze key problem features (e.g., size of unit digits) with sufficient depth to choose the better strategy on each problem.

Regarding age-related differences in how emotions affect strategy selection, we expected young adults' strategy selection to be more influenced by negative emotions than older adults'. This would be seen if differences in mean percentages of better strategy selection between negative and neutral emotion conditions are larger in young than in older adults. As discussed earlier, such smaller influence of negative emotions in older adults would be consistent with previous findings of age-related positivity effects showing that older adults are less influenced by negative emotions than young adults'. Alternatively, if emotions influence young and older adults' strategy selection to the same extent, we expected that poorer strategy selection under negative emotions would be similar in young and older adults.

Method

Participants

A total of 58 participants were tested: 29 young and 29 older adults (see participants' characteristics in Table 1). Our target sample size was determined using an a priori power analysis (G*Power; Faul et al., 2007). Although no previous studies tested age-related differences in effects of emotions on strategy selection, we used η_p^2 from previous studies on age-related differences in better strategy selection. Previous results on better strategy selection during computational estimation tasks in young and older adults found that η_p^2 ranged from .19 to .26 (e.g., Lemaire et al., 2004). Using a $\eta_p^2 = .19$, our study design of one between-participant factor (age) and two with-participants factor (emotion and problem difficulty) could achieve 90% power with 48 participants. In order to exceed this criterion and achieve more than 90% power, we recruited 58 participants.

Stimuli for the Computational Estimation Task

Following previous works (e.g., Hinault et al., 2017; Lemaire & Brun, 2016; Lemaire & Leclère, 2014; Nicolas et al., 2021), the computational estimation task included 48 two-digit multiplication problems (e.g., 34 × 67; see the list of problems in Table S2 in the online supplemental materials), each solved under negative and neutral emotion condition. Based on which strategy yielded the better estimate for each problem, two types of problems were selected. The better strategy was easier to select on the so-called easier problems (e.g., 26 × 71) than on the so-called harder problems (e.g., 24 × 69). Absolute differences in mean percent deviations between correct products and estimates with the rounding-down and rounding-up strategies were larger for easier than for harder problems. Thus, mean differences between the rounding-up and rounding-down strategies were 10.3%, for easier problems (corresponding *SD*s = 2.18, and min–max = 6.76–14.64) and 0.7% for harder problems (corresponding *SD*s = 0.58, and min–max = 0.4–2.25). Half the easier and harder problems were better estimated with the rounding-down strategy and half with the rounding-up strategy. Like in Experiment 1, the selection of problems was further constrained by previous findings in arithmetic, as indicated in the note of Table S1 in the online supplemental materials.

Stimuli for Emotional Pictures

Eighty pictures were selected from the IAPS (Lang et al., 2008). Half the pictures depicted negative events (e.g., a snake) and half neutral events (e.g., a chair). Emotional valence and arousal were matched across each problem type (see Table 2).

Procedure

The same procedure as in Experiment 1 was used, except that participants accomplished a computational estimation task instead of a two-digit addition problem-solving task. They were asked to provide the best estimate on each problem using either a rounding-up or a rounding-down strategy. Like in previous works using this task, the rounding-down strategy was described as "rounding both operands down to their nearest decades, for instance doing 80 × 20 to estimate 876 × 26," and the rounding-up strategy as "rounding both operands up to their nearest decades, for instance doing 90 × 30" (e.g., Nicolas et al., 2021, p. 442). Participants were informed that for each problem, either rounding down or rounding up was the better strategy. They were asked to try to select the better strategy among these two in order to find the best estimate for each problem. Participants were explicitly told that the better strategy was to round one operand down and the other up to their nearest decades (e.g., 34 × 19) for all problems, but that this mixed-rounding strategy was not allowed. This mixed-rounding strategy was not allowed to make the strategy choice process harder, given that previous studies showed that when participants can use mixed-rounding, strategy selection is so easy that everybody select the better strategy on more than 95% of problems (e.g., Lemaire et al., 2004). Like in Experiment 1, to make sure that participants processed the emotional pictures, they were asked to accomplish a picture judgment task (i.e., saying whether the two images were the same or different). They were correct on 99% of trials, and provided their judgment faster on neutral than on negative emotion pictures, 898 ms versus 860 ms, $F < 1.0$.

Half the problems were estimated in the negative emotion condition (i.e., with a negative picture) and the other problems in the neutral condition (i.e., with a neutral emotion picture). The number of rounding-down and rounding-up problems and on mean correct products were matched across neutral and negative emotion conditions. Problems were randomly presented to participants, with the constraints that no more than three images involved the same emotion and that the same rounded operands did not occur on two successive problems.

Before the computational estimation task starts in earnest, participants underwent a practice session. Following description of the rounding-down and the rounding-up strategies and illustration with two examples for each strategy, participants practiced the rounding-down and rounding-up strategies on five problems each. Then, they practiced the task on eight problems to familiarize themselves with the procedure and the tasks. Following this practice session, participants saw two blocks of 48 trials each, with a brief pause in-between each block. They were asked to estimate out loud to determine which strategy they used. Participants used no other strategies than rounding down or rounding up. In both Experiments 2 and 3, equal emphasis was placed on latency and accuracy, as participants were told that "you should try to find the best estimate as quickly as you can with RD/RU strategy."

Results

Results are reported in two main parts. The first part analyzes age-related differences in how emotions influence participants' better strategy selection and the second examines age-related differences in effects of emotions on participants' performance. Performance measures included mean solution times and percent deviations (between exact products and participant's product estimates). Percent deviations were calculated as follows: [(exact product − estimate)/estimate) × 100]. For example, a participant providing 2,500 as an estimate for 43 × 69 would be [(2,967–2,500)/2,967] × 100 = 15.7% away from the exact product. Estimation performance (i.e., mean estimation latencies and absolute percentages of deviations) and mean percentages of better strategy use were analyzed with mixed-design ANOVAs, 2 (age: young, older adults) × 2 (problem difficulty: easier, harder) × 2 (emotion: neutral, emotion), with repeated measures on the last two factors (see means in Table 7). Effects of emotion were further examined with separate analyses in each age group, followed by neutral–negative pairwise comparisons.

Age-Related Differences in Effects of Emotions on Better Strategy Use

Participants selected the better strategy less often in the negative emotion condition than in the neutral emotion condition (58.9% vs. 64.8%), $F(1, 56) = 113.660$, $MSE = 17.740$, $\eta_p^2 = .690$, $p < .001$, and on harder than on easier problems (73.4% vs. 49.9%), $F(1, 56) = 127.430$, $MSE = 47.540$, $\eta_p^2 = .690$). Main effects of emotion were significant in both young adults (61.4% vs. 67.0%), $F(1, 28) = 48.430$, $MSE = 18.390$, $\eta_p^2 = .630$, $p < .001$, and older adults (56.3% vs. 62.6%), $F(1, 28) = 66.300$, $MSE = 17.090$, $\eta_p^2 = .700$, $p < .001$. Also, the main effects of problem difficulty were significant in both young (77.1% vs. 51.4%), $F(1, 28) = 48.430$, $MSE = 42.520$, $\eta_p^2 = .630$, $p < .001$, and older adults (73.4% vs. 49.9%), $F(1, 28) = 91.600$, $MSE = 52.560$, $\eta_p^2 = .770$, $p < .001$. No other main or interaction effects came out significant on mean percent use of the better strategy. Thus, both young and older adults selected the better strategy less often in the negative emotion condition than in the neutral emotion condition, whether the better strategy was easier or harder to select.

Table 7
Mean Percent Use of the Better Strategy, Estimation Times, and Absolute Percentages of Deviations on Easier and Harder Problems in Neutral and Negative Emotion Conditions for Young and Older Adults, in Experiment 2

	Young adults			Older adults		
Problem difficulty	Neutral	Negative	Negative–neutral	Neutral	Negative	Negative–neutral
Better strategy selection (%)						
Easier	79.3	74.6	−4.7**	73.7	67.4	−6.3**
Harder	54.5	48.1	−6.4**	51.4	45.3	−6.2**
Means	66.9	61.4	−5.6	62.6	56.3	−6.3
Estimation latencies (in ms)						
Easier	6,060	6,027	−33	8,198	8,028	−170
Harder	6,132	5,991	−131	8,272	8,027	−245
Means	6,096	6,009	−81	8,235	8,017	−208
Percentages of deviations						
Easier	16.8	17.4	0.6**	17.4	17.9	0.5**
Harder	19.8	19.8	0.1	19.8	19.8	0.0
Means	18.3	18.6	0.2	18.6	18.8	0.2

** $p < .01$.

Age-Related Differences in Effects of Emotions on Performance

No effects came out significant on estimation latencies (Fs < 1.88).

Participants provided poorer estimates in the negative emotion condition than in the neutral emotion condition (18.7% vs. 18.4%), $F(1, 56) = 14.100$, $MSE = 0.270$, $\eta_p^2 = .200$, $p < .001$, and on harder than on easier problems (19.8% vs. 17.4%), $F(1, 56) = 97.330$, $MSE = 3.530$, $\eta_p^2 = .630$, $p < .001$. Moreover, the Problem Difficulty × Emotion interaction came out significant, $F(1, 58) = 11.060$, $MSE = 0.330$, $\eta_p^2 = .160$, $p = .002$. This interaction showed that the effect of emotions was significant for easier, $F(1, 56) = 14.171$, $MSE = 0.523$, $\eta_p^2 = .202$, $p < .001$, but not for harder problems ($F < 1.0$). These effects of emotion, problem difficulty, and Problem Difficulty × Emotion were significant in both young and older adults (Fs > 4.61).

Discussion

The present data bring support to the hypothesis that emotions influence strategy selection. Indeed, negative emotions had deleterious effects on how often participants selected the better strategy on each problem. Young and older adults found approximate products to two-digit multiplication problems with the better strategy less often under the negative emotion condition than under the neutral emotion condition. This occurred to the same extent in young and older adults and while solving easier or harder problems.

Deleterious effects of emotions on participants' performance were found on mean percent deviations (but not on estimation latencies) only for easier problems, and not for harder problems. This is surprising because emotions influenced better strategy selection on both easier and harder problems. This should have led participants to provide poorer estimates under negative emotions for both easier and harder problems. However, it is possible that differences in efficient execution of strategies for easier and harder problems may have masked deleterious effects of emotions while participants solved harder problems. This can occur if participants executed the better strategy more poorly under negative emotions while solving easier problems but not while solving harder problems.

One limitation of Experiment 2 is that differences in participants' performance under negative and neutral emotion conditions are accompanied by differences in both better strategy selection and strategy execution. This is because strategy execution is not assessed independently of strategy repertoire and strategy selection. This may also explain why we found no effects of emotions on estimation latencies, making it impossible to determine whether participants are slower while executing strategies under negative emotion condition than under neutral emotion condition. To compare participants' performance under negative and neutral emotion conditions, and to determine if effects of emotions on participants' performance vary with the type of strategy, the type of problem, and participants' age, performance should be assessed under negative and neutral emotion conditions for each strategy independently of strategy selection and strategy repertoire. This was the goal of Experiment 3.

Experiment 3: Aging, Emotions, and Strategy Execution

Experiment 3 aimed at determining whether negative emotions influence strategy execution and whether this influence changes with participants' age. Like in Experiment 2, we asked young and older adults to do computational estimation tasks on two-digit multiplication problems (e.g., 38 × 64). This task was used because it is easy to ask participants to execute a given strategy on each problem and control that they comply with instructions. This is important if we want to assess the role of emotions on strategy execution. The same set of problems was solved with each strategy by each participant under both emotion conditions. This allows to compare young and older adults' performance in neutral and negative emotion conditions for different types of problems and strategies, all else being equal.

The hypothesis that negative emotions impair strategy execution predicts that participants will provide poorer estimates and take longer to estimate under negative emotion conditions, especially for harder problems. Like for strategy repertoire (Experiment 1) and strategy selection (Experiment 2), this would occur if emotions capture attentional resources and fewer resources are left free to execute strategy components (e.g., encoding problems, rounding both operands, calculating products of rounded operands, and providing estimates). Execution of the harder, rounding-up strategy is expected to be more impaired under negative emotions than execution of the easier rounding-down strategy. This should happen as a result of the harder strategy requiring more resources and processing resources being depleted by emotional capture. Both previous empirical works on strategy performance and theoretical analyses of strategy components (e.g., Hinault et al., 2017; Lemaire et al., 2004; Nicolas et al., 2021) showed that the rounding-up strategy is harder to execute than the rounding-down strategy.

Regarding age-related differences in how emotions change strategy execution, we expected older adults' to be less impaired by negative emotions than young adults' while executing strategies. This would be seen if differences in mean percentages of deviations and/or in estimation latencies between negative and neutral emotion conditions are smaller in older adults than in young adults. Smaller influence of negative emotions on older adults' strategy execution than on young adults' would extend to strategy execution age differences found in Experiment 1 on strategy repertoire. As discussed earlier, such smaller influence of negative emotions in older adults would be consistent with previous findings of age-related positivity effects showing that older adults are less affected by negative emotions than young adults'. Alternatively, if emotions influence young and older adults' strategy selection similarly like it does for strategy selection (Experiment 2), poorer strategy selection under negative emotions should be similar in young and older adults.

Method

Participants

A total of 58 participants were tested: 29 young and 29 older adults (see participants' characteristics in Table 1). Our target sample size was determined using an a priori power analysis (G*Power; Faul et al., 2007). Although no previous studies tested age-related differences in effects of emotions on strategy execution, we used η_p^2 from previous studies on age-related differences in strategy execution. Previous results on better strategy execution during computational estimation tasks in young and older adults found that η_p^2 ranged from .21 to .36 (e.g., Lemaire et al., 2004). Using a $\eta_p^2 = .21$, our study design of one between-participants factor (age) and two within-participants factors (problem difficulty, emotion) could achieve 90%

power with 56 participants. In order to exceed this criterion and achieve more than 90% power, we recruited 58 participants.

Stimuli and Procedure

The same problems and images, as well as the same sequence of events within a given trial as in Experiment 2 were used. The only difference was that participants did not have to select strategies on each problem but were told which strategy to execute. The set of 48 problems was divided into two matched subsets, subset A and subset B. In each subset, half the problems were best estimated by the rounding-down strategy and the other problems by the rounding-up strategy. Half the participants were asked to execute the rounding-down strategy to find estimates of all problems in subset A (once under neutral and once under negative emotion conditions, randomly presented) and to execute the rounding-up strategy on all problems in subset B (also once under neutral and once under negative emotion conditions, randomly presented). The other participants did the reverse. Half the participants executed the rounding-down strategy first and the rounding-up strategy second; the other participants did the reverse. Participants first practiced each strategy on 10 problems. They had no difficulties in following instructions requiring them to use the rounding-up and rounding-down strategies on the whole set of problems, both during training and the experiment.

Results

Mean estimation times and percent deviations between estimates and expected products given the instructed strategy were analyzed with mixed-design ANOVAs, 2 (age: young, older adults) × 2 (strategy: rounding-down, rounding-up) × 2 (emotion: neutral, emotion), with repeated measures on the last two factors (see means in Table 8). Preliminary analyses included the type of problems as a within-participants factor. However, this factor was not significant and was not involved in any significant interaction. Therefore, analyses of performance are reported collapsed over problem type.

Participants were slower in the negative emotion condition than in the neutral emotion condition (4,230 ms vs. 3,928 ms), $F(1, 56) = 69.15$, $MSE = 76{,}585.120$, $\eta_p^2 = .550$, $p < .001$, and with the rounding-up strategy than with the rounding-down strategy (4,749 ms vs. 3,409 ms), $F(1, 56) = 66.640$, $MSE = 161{,}000$, $\eta_p^2 = .540$, $p < .001$. Most interestingly, the Age × Emotion interaction came out significant, $F(1, 56) = 4.130$, $p = .050$, $MSE = 76{,}585.120$, $\eta_p^2 = .07$, $p = .050$. Although main effects of emotions were significant in both age groups (Fs > 18.610), young adults increased their latencies in negative emotion relative to neutral emotion condition more than older adults (+376 ms vs. +228 ms). Also, the Strategy × Emotion was marginally significant, $F(1, 56) = 3.670$, $MSE = 152{,}454.630$, $\eta_p^2 = .06$, $p = .060$, as the effects of negative emotions tended to be larger for the harder, rounding-up strategy (+400 ms) than for the easier, rounding-down strategy (+204 ms).

The main effect of strategy (1.3% vs. 3.2%), $F(1, 56) = 16.690$, $MSE = 13.050$, $\eta_p^2 = .230$, $p < .001$, and the Age × Strategy interaction, $F(1, 56) = 3.90$, $MSE = 13.050$, $\eta_p^2 = .070$, $p = .050$, came out significant on mean percent deviations. This interaction resulted from older adults providing poorer estimate with the rounding-up strategy than with the rounding-down strategy (2.6%), $F(1, 28) = 13.730$, $MSE = 8.640$, $\eta_p^2 = .330$, $p < .001$, and younger adults' estimates being similarly close to correct products with the rounding-down and rounding-up strategies (1.0%), $F(1, 28) = 3.70$, $MSE = 8.640$, $\eta_p^2 = .110$, $p = .080$. No other effects came out significant on latencies or percentages of deviations.

In sum, both young and older adults were slower while executing strategies under the negative and neutral emotion condition, and they were slowed down somewhat more while executing the harder, rounding-up strategy relative to the easier, rounding-down strategy. Also, older but not young participants provided poorer estimates with the harder than with the easier rounding strategy.

Distributional Analyses of Emotion Effects

We used the so-called vincentization technique (Ratcliff, 1979) to characterize the dynamics of the emotion effects on strategy execution and to compare these dynamics in young and older adults. We analyzed distributions of the emotion effects (i.e., latencies for emotion trials − latencies for neutral trials) as a function of the overall distribution of latencies. The latencies for correctly executed strategies were sorted in ascending order and binned in four classes of equal size ($N = 12$ observations/bin maximum). The mean of each bin (henceforth referred to as quartiles) was computed separately for each participant and each strategy in each emotion condition. Average distributions of latencies were obtained by computing the mean values of quartiles by emotion condition (neutral, emotion), strategy (rounding-down, rounding-up), and age group (young, older adults) separately.

Emotion effects were analyzed with 2 (age: young, older adults) × 2 (strategy: rounding-down, rounding-up) × 4 (quartile: first, second, third, and fourth) ANOVA, with age as the only between-participants factor. The main effects of quartile, $F(3, 168) = 15.096$, $MSE =$

Table 8
Mean Estimation Latencies in Milliseconds and Percentages of Deviations in Young and Older Adults for Each Rounding Strategy Under Neutral and Negative Emotion Conditions, in Experiment 3

	Young adults			Older adults		
Strategy	Neutral	Negative	Negative–neutral	Neutral	Negative	Negative–neutral
Estimation latencies (in ms)						
Rounding down	3,306	3,547	241	3,308	3,476	167
Rounding up	4,521	5,032	511	4,576	4,865	289
Means	3,914	4,290	376	3,942	4,170	228
Percentages of deviations						
Rounding down	1.3	1.4	0.1	1.0	1.4	0.4
Rounding up	2.4	2.3	−0.1	3.7	4.4	0.7
Means	1.8	1.9	0.1	2.4	2.9	0.5

Note. Strategy differences: rounding up–rounding down.

382,165.529, $p < .001$, $\eta_p^2 = .757$, and of strategy, $F(1, 56) = 4.606$, $p = .036$, $MSE = 1{,}401{,}543.558$, $\eta_p^2 = .076$, as well the Strategy × Quartile interaction, $F(3, 168) = 3.614$, $MSE = 564{,}291.065$, $p = .015$, $\eta_p^2 = .061$, were significant. Finally, the Strategy × Quartile interaction was significant in young adults, $F(3, 84) = 4.283$, $MSE = 716{,}019.853$, $p = .007$, $\eta_p^2 = .133$, but not in older adults, $F < 1.0$. As can be seen in Figure 2, emotion effects increased with increasing latencies while executing the harder, rounding-up (but not while executing the easier, rounding-down) strategy in young adults and while executing both rounding strategies in older adults.

Discussion

The present data bring support to the hypothesis that emotions influence strategy execution. Indeed, negative emotions had deleterious effects on participants' latencies (but not on percent deviations). Participants were slower while estimating two-digit multiplication products under negative emotion than under neutral emotion condition. Most interestingly, deleterious effects of emotions were larger in young than in older adults. Finally, deleterious effects of emotions on participants' latencies increased in both age groups when participants needed more time to execute either strategy (except when young adults executed the easier, rounding-down strategy).

Interestingly, the deleterious effects of negative emotions on participants' performance, and age-related differences therein, could not come from different strategies being used under each emotion condition and by each age group or from different strategy distributions across age groups and emotion conditions. By requiring all young and older individuals to execute strategies on all problems, any emotion-related differences can be assumed to result from effects of emotions on strategy execution.

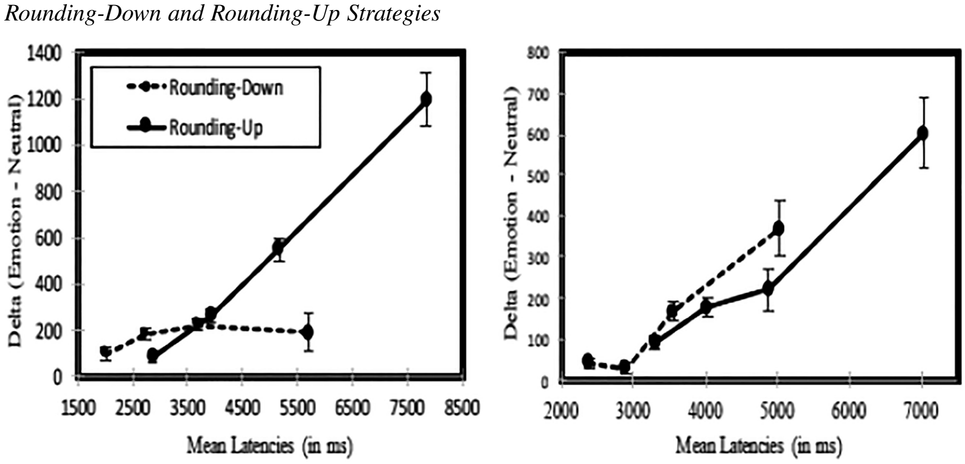
Note that emotions influenced latency but not percent deviations. This occurred most likely because both young and older adults were careful in executing strategies as accurately as possible, making the latency variable most sensitive to effects of emotions and percent deviation insensitive. When effects of emotions were examined as a function of participants' mean latencies, deleterious effects of emotions were larger for problems that participants take more time to solve. Most likely, relative to problems that participants are quicker to solve, these problems place heavier demands on cognitive resources. With fewer resources available following or concurrent to emotional processing, participants are slowed down while finding estimates on these problems.

General Discussion

In three experiments, I examined the role of emotions in arithmetic and investigated how this role changes with aging. I adopted a strategy approach and examined strategic aspects of participants' performance under emotionally neutral and negative conditions. More specifically, I determined whether negative emotions influence strategy repertoire (i.e., which strategies are used and how many strategies individuals rely on), strategy distribution (i.e., how often each strategy is used), strategy selection (i.e., how often is the better strategy chosen on each problem), and strategy execution (i.e., how efficient strategies are). Age-related differences in how emotions influence strategic aspects of cognitive performance were tested in arithmetic, a domain in which older adults most often obtain as good, and sometimes even better, performance as young adults. Participants solved two-digit addition problems (Experiment 1) or accomplished computational estimation tasks (Experiments 2 and 3). The results showed that negative emotions influenced all four strategy dimensions (i.e., repertoire, distribution, execution, and selection) examined here. Moreover, emotions had different effects in young and older adults on strategy repertoire, distribution, and execution, and similar effects on strategy selection. Because these data suggest that emotions influence how participants accomplish cognitive tasks, and differently so during aging, they have important implications to further our understanding of the effects of emotions on participants' cognitive performance and how these effects change with aging. I next discuss these implications.

Figure 2

Distributions of Emotion Effects (Delta Plots) in Young and Older Adults While Executing the Rounding-Down and Rounding-Up Strategies



Note. This plot shows how the size of emotion effects (differences in latencies between emotion and neutral conditions) varies as a function of the overall distribution of latencies for the first, second, third, and fourth quartiles in each age group and for each strategy.

How Emotions Influence Cognition

A number of studies investigated effects of emotions on cognition and found that emotions sometimes increase and sometimes decrease cognitive performance (see De Houwer & Hermans, 2010; Lemaire, 2022a; Robinson et al., 2013). Emotions are also associated with changes in brain activations while participants accomplish cognitive tasks (Dolcos et al., 2022). Above and beyond determining whether emotions increase or impair performance and influence brain activations while participants accomplish cognitive tasks, and when it does so, it is important to determine the responsible mechanisms to account for emotion–cognition interactions. By documenting how emotions affect strategy repertoire, distribution, execution, and selection, the strategy perspective adopted here is fruitful to reach this goal of providing a mechanistic account of how emotions influence cognition.

Negative emotions led participants to (a) use fewer strategies and change how often they used each available strategy (Experiment 1), (b) select the better strategy on each problem less often while solving both easier and harder problems (Experiment 2), and (c) obtain poorer performance under negative emotion conditions, especially on problems that participants needed more time to solve (Experiments 1 and 3), even when strategy repertoire, distribution, and selection did not differ in emotionally negative and neutral conditions (Experiment 2).

Deleterious effects of negative emotions on participants' performance are consistent with previous findings both in arithmetic (Fabre & Lemaire, 2019; Framorando & Gendolla, 2018, 2019; Lallement & Lemaire, 2021; Lemaire & Brun, 2018; T. Liu et al., 2011; Melani et al., 2023; Schimmack & Derryberry, 2005) and in other cognitive domains (see De Houwer & Hermans, 2010; Lemaire, 2022a; Robinson et al., 2013 for overviews). Like in previous studies, deleterious effects of negative emotions were larger on problems that participants needed more time to solve. What is unique here is that these deleterious effects were found when all participants had to use both rounding strategies on all problems in Experiment 3, thereby controlling for emotion-related differences in strategy repertoire, distribution, and selection. This suggests that when emotions impair cognitive performance, they lead participants to more poorly execute the strategies they use to accomplish a cognitive task, even when they use the same strategies under neutral and emotion conditions, as well as when all strategies equally often and on the same items. With all strategic aspects, but strategy execution, kept constant, the present deleterious effects of negative emotions on participants' performance are consistent with the general attentional capture mechanism, most usually assumed to be responsible for deleterious effects of emotions on cognition (Okon-Singer et al., 2015; Verbruggen & De Houwer, 2007). Thus, attention captured by negative emotional processing leads to poorer strategy execution.

Unknown is whether emotions impair execution of some specific procedures or all procedures within each strategy. As a strategy is "a procedure or a set of procedures for achieving a higher-level goal or task" (Lemaire & Reder, 1999, p. 365) it is possible that emotions influence some procedures and do not impair execution of other procedures while participants execute strategies. Future research may examine this issue by comparing effects of emotions on component procedures of strategies. This can be done in arithmetic as well as in any other cognitive domain by manipulating factors that are known to affect specific procedures. Examples in computational estimation tasks like those in the present experiments include manipulating the size of decade digits in two-digit multiplication problems, known to influence calculation of rounded operands or size of the unit digits known to affect difficulty of rounding. In this vein, future research may examine other strategies that were not investigated here, like mixed-rounding strategy (in computational estimation tasks) or retrieval versus nonretrieval strategies (in simple arithmetic problem-solving tasks).

Above and beyond their effects on performance, negative emotions influenced participants' strategy repertoire and distribution. When they were free to choose whichever strategy they wanted on each two-digit addition problem in Experiment 1, young participants reduced their strategy repertoire and used fewer strategies under negative emotions. They also did not use available strategies equally often under neutral and negative emotion conditions. Given that using a larger-strategy repertoire requires more resources (to maintain multiple strategies activated in working memory, to switch and choose among several strategies from one trial to the next), smaller strategy repertoire under negative emotions most likely stemmed from fewer available resources as a result of emotional processing capturing some of these resources. Also, using some strategies more often (e.g., rounding the first operand) and others less often (e.g., columnar retrieval) in Experiment 1 may have helped participants manage strategy choices under negative emotions. In sum, emotions changed participants' performance. They also changed how they accomplished the present arithmetic problem-solving tasks.

The present emotion-related changes in strategy repertoire and strategy distribution may not be unique to arithmetic. They most likely generalize to other cognitive domains. This issue may be examined in future empirical studies by using the same strategy assessment method as the one used here that allowed identification of which strategy was used on each trial. Only by assessing strategies on a trial-by-trial basis shall we be able to know how participants accomplish a cognitive task under emotion conditions and whether this differs with what they actually do under emotionally neutral conditions. Given that strategies differ in relative efficiency and involve different cerebral networks, we will be better able to go beyond saying that negative emotions impair performance and change brain activations. We will also be able to go beyond explanations of effects of emotions in terms of general processing resources and provide more fine-grained mechanistic accounts.

Negative emotions also influenced strategy selection. Participants used the better strategy less often on each problem in the negative emotion condition of Experiment 2 in which they had to find approximate products of two-digit multiplication problems and could choose among two rounding strategies only. Restricting the strategy repertoire to strategies that participants are known to spontaneously use to accomplish a given cognitive task made sure that any emotion-related differences in how often they selected the better strategy could not stem from differences in the number and type of strategies used by participants across emotion conditions.

This constraint is important to test whether emotions influence strategy selection mechanisms. Following the present emotion-related differences in strategy selection, it is important to next determine how could negative emotions lead participants to select the better strategy on each problem less often. Several strategy selection mechanisms can be tested in future research, including both domain-general and domain-specific mechanisms. Examples of domain-general mechanisms include executive control, working-memory resources, and metacognitive mechanisms. Indeed, previous works suggest that mechanisms like executive control or processing speed (e.g., Ardiale et al., 2012; Hodzik & Lemaire, 2011; Lemaire & Lecacheur, 2011) working-memory resources (e.g., Barrouillet & Lépine, 2005; DeStefano & LeFevre, 2004; Peng et al., 2016), or metacognition (e.g., Castel et al., 2015; Geurten et al., 2018; Geurten & Lemaire, 2017, 2023; Hertzog, 2016) crucially involved in better strategy selection, may be influenced by emotions. Example of domain-specific mechanisms that could be influenced by emotions include analyzing semantic features of problems (e.g., size of the unit digits in both operands), carry-over processing, or more generally domain-specific expertise.

Age-Related Changes in How Emotions Influence Cognition

Previous works found that emotions sometimes modulate age-related differences in cognition and that young and older adults can be differently influenced by emotions (Dolcos et al., 2014; Gutchess, 2019; Lemaire, 2022a; Reed & Carstensen, 2012). In addition to knowing whether effects of emotions on young and older adults' cognitive performance are similar or different and how emotions modulate cognitive aging, it is important to determine whether emotions influence cognition via the same or different mechanisms in young and older adults. Examining strategic aspects of young and older adults' performance under emotionally neutral and negative conditions in the present experiments yielded data suggesting that the mechanisms via which emotions influence cognition change with aging.

In the present experiments, we found both differences in effects of emotions on some strategy dimensions and similar effects on other strategy dimensions in young and older adults. More specifically, negative emotions (a) influenced efficiency of strategy execution less strongly in older adults than in young adults, as decreased performance under negative emotions was larger in young than in older adults, (b) affected young adults' strategy repertoire but not older adults', as only young adults used fewer strategies under negative emotion conditions, (c) changed strategy distributions more strongly in younger than in older adults, as only older adults increased their use of borrowing unit to solve two-digit addition problems (Experiment 1) whereas young adults increased their use of borrowing unit and rounding the first operand, and decreased their use of columnar retrieval and rounding the second operand, and (d) influenced strategy selection to the same extent in both age groups, as both young and older adults were comparable in selecting the better strategy on each item less often under negative emotions.

The present data replicated previous findings of smaller deleterious effects of negative emotions on performance in older than in young adults, both in arithmetic (Lallement & Lemaire, 2021; Melani et al., 2023) and in cognition in general. Our results follow general patterns of findings regarding age-related changes in emotion–cognition relations. In particular, age-related positivity effects robustly found in many cognitive domains (Mather, 2012; Reed & Carstensen, 2012) showed that older adults are less influenced by negative emotions than young adults (and more influenced by positive emotions) when they accomplish cognitive tasks. Unknown was whether such age-related differences in effects of emotions on cognitive performance would be observed when other strategy dimensions (i.e., repertoire, distribution, selection) are controlled. This was found here as smaller effects of negative emotions on older adults' performance compared to young adults' occurred even when age differences in strategies were controlled (Experiment 3).

Smaller effects of negative emotions during arithmetic may stem from older adults' attention being less captured than young adults' by negative stimuli. It is also possible that both young and older adults' attention was similarly grabbed by negative pictures but that older adults regulated negative emotions more efficiently than young adults. Older adults are known to be sometimes better at emotional regulation than young adults (e.g., Lohani & Isaacowitz, 2014; Nashiro et al., 2012; Scheibe et al., 2015; Shiota & Levenson, 2009; Urry & Gross, 2010). Here, this could happen if older adults strategically disengaged more quickly than young adults from negative stimuli processing and focused more quickly on arithmetic problem solving. Future studies may tease apart lower attentional capture by emotional stimuli and better strategy regulation in older adults.

The other interesting and original findings in the present experiments concern age-related differences in effects of emotions on strategy selection and strategy repertoire. Strategy selection was affected by emotions in both young and older adults, whereas strategy repertoire was influenced in young adults only. Even if effects of emotions on strategy selection were comparable in both age groups, this could occur via emotions influencing either the same or different strategy selection mechanisms in young and older adults. Indeed, previous studies established that strategy selection involves several mechanisms, including both domain-general mechanisms (e.g., executive control, working-memory resources, metacognition) and domain-specific mechanisms (e.g., problem feature analyses; magnitude processing). Comparing effects of emotions on these mechanisms in young and older adults while participants accomplish cognitive tasks in which they are asked to select the better strategy on each item will enable to know whether emotions influence the same or different strategy selection mechanisms in young and older adults.

Finally, negative emotions did not have the same influence on young and older adults' strategy repertoire. Young adults used fewer strategies under negative than under neutral emotion conditions in Experiment 1 whereas older adults used an equal number of strategies under both conditions. This does not mean that emotions have no influence on the number of strategies used by older adults in all cognitive domains. Also, note that the same set of nine strategies used to find sums of two-digit addition problems was observed in both age groups under neutral and emotion conditions. This does not discard the possibility that, in some domains, emotions lead participants to use different sets of strategies. That emotions influence the number of strategies in young adults only and does not affect the set of strategies in both young and older adults may be specific to some cognitive domains (like arithmetic) and not to other domains is a possibility that future studies may examine.

Constraints on Generality

The present findings showed effects of emotions on strategic aspects of young and older adults' arithmetic performance. Effects of emotions were investigated via comparing neutral and negative emotions. As different categories of negative emotions were not compared, one of the next important steps would be to determine whether the present findings generalize across all types of negative emotions (e.g., fear, disgust, sadness) and are modulated by the type of negative emotions (vs. are specifics to one type of negative emotions). Also, important is to determine whether effects of emotions on strategic aspects of performance are similar or different for positive and negative emotions and for emotions of varying levels of arousal. Additionally, our emotional stimuli involved negative and neutral pictures displayed before and while participants solve arithmetic problems. Such procedure and different variants (e.g., videos or narratives inducing emotions) have been used in numerous previous research and yielded highly reproducible effects of emotions. I anticipate that different types of emotional stimuli and procedure for emotional induction would yield similar patterns of findings.

The present studies were carried out in the domain of arithmetic. As previous research in arithmetic found that findings in this domain most often generalize to other cognitive domains and as previous research across the board of human cognition found that strategy variability is a key feature of human cognition, I have no reasons to think that the present effects of emotions on strategic aspects of cognitive performance do not generalize to other cognitive domains. Of course, studies examining how emotions affect strategy repertoire, distribution, selection, and execution in different cognitive domains will be able to document both domain-general and domain-specific features of how emotions influence strategic aspects of cognition.

Finally, the present findings showed that negative emotions influenced young and older participants' performance and strategy selection to the same extent, and that young adults' strategy repertoire, distribution, and execution were more affected than older adults'. I have no reasons to think that larger effects of emotions in young than in older adults are specific to context (i.e., the domain of arithmetic, with computational estimation and addition problem-solving tasks, with groups of undergraduates as young adults and healthy older adults matched on levels of education). Indeed, previous studies in a wide variety of cognitive domains have found that young adults' cognitive performance is very often more influenced by negative emotions than older adults', an effect referred to as "age-related positivity bias." Future studies may further test the generality of the present findings in different populations of young adults (e.g., varying in emotional sensitivity, regulation, and arithmetic proficiency) and older adults (e.g., varying in levels of cognitive efficiency or health) and may determine whether age-related differences in effects of emotions occur on the same versus different strategic aspects of performance across cognitive domains.

All in all, I have no reasons to believe that the results reported here are specific to the samples of participants tested in the present experiments, or to the materials, domain, or situations used here.

Conclusion

Effects of emotions on cognition and age-related differences therein that have been found in a wide variety of domains can be associated with more specific effects of emotions on strategic aspects of cognitive performance: decrease in the number of strategies, changes in the type of strategies, greater use of some strategies and lower use of other strategies, impaired strategy execution, and less frequent selection of the better strategy. In this study, negative emotions influenced all these strategy dimensions, except the type of strategy. Also, emotions influenced strategy execution more strongly in young than in older adults, the number of strategies only in young adults, and strategy selection similarly in both age groups. These findings suggest that the present strategy approach as well as methods of assessing strategy use on a trial-by-trial basis (Experiments 1 and 2) and of instructing which strategy to use (Experiment 3) might be fruitful to further our understanding of how emotions influence cognition and of age-related differences in this influence, not only in the context of arithmetic, but in a variety of other domains as well.

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