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How Emotions Modulate Arithmetic Performance

A Study in Arithmetic Problem Verification Tasks

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Abstract: The goal of the present study was to test whether and how emotions influence arithmetic performance. Participants had to verify arithmetic problems. True-problems were either easier or harder problems. False-problems were parity-match or parity-mismatch problems. The odd/even status of proposed and correct answers was the same in parity-match problems (e.g., $19 \times 7 = 131$) and different in parity-mismatch problems (e.g., $17 \times 9 = 152$). Before each problem, participants saw a positive (e.g., smiling baby), negative (e.g., mutilations), or neutral pictures (e.g., neutral face) selected from International Affective Picture System (IAPS). They had to decide whether each picture includes a person or not before verifying each arithmetic problem. Results showed different effects of emotion on true- and false problem verification. Participants' performance on true-problems showed decreased problem-difficulty after processing negative pictures and increased difficulty effects after processing positive pictures. On false-problems, we found smaller parity-violation effects after negative pictures (i.e., decreased performance on parity-mismatch problems), together with larger parity-violation effects after positive pictures (i.e., decreased performance on parity-match problems). These findings suggest that emotions influence arithmetic performance via which strategy is used and how each strategy is executed on each problem. They have important implications for understanding the role of emotions on arithmetic performance, and more generally on how emotions influence cognition.

Keywords: arithmetic, emotion, strategy



The goal of the present study was to test whether and how emotions influence arithmetic performance. Although effects of emotions on cognitive performance have been documented in a wide variety of cognitive domains, surprisingly little research has examined these effects in the domain of arithmetic. As a consequence, we ignore whether emotions influence arithmetic performance, and if yes, what are the underlying mechanisms. The goal of this study was to investigate these issues. We first briefly review previous findings on emotions and cognition. Then, we discuss why it is relevant to determine whether emotions influence arithmetic performance and describe the logic of the present work.

A number of previous studies found that emotions influence cognitive performance in a wide variety of cognitive domains, including attention, memory, reasoning, problem solving, and decision-making (see Robinson, Watkins, &

Harmon-Jones, 2013, for an overview). Thus, previous studies found that emotion can influence cognitive performance, narrow the scope of attention, lead participants to process more deeply and better remember some (emotional) stimuli than other (neutral) stimuli, disrupt perception of some stimuli or aspects of stimuli, hinder logical reasoning, or bias decision making. Also, emotions have been found to enhance cognitive performance in some contexts (e.g., when emotionality of content matches participants' mood) (e.g., Blanchette & Campbell, 2012; Blanchette & Caparos, 2013; Blanchette, Richards, Melnyk, & Lavda, 2007). As an illustrative example of effects of emotions on cognitive performance, Waring and Kensinger (2009) tested effects of emotions on memory. Participants viewed scenes including central emotion information (e.g., a snake) and peripheral non-emotional, neutral background information (e.g., riverside). Central emotional information could be positive (e.g., kitten), negative (e.g., snake), or neutral (e.g., chipmunk). Recognition memory was tested separately for central and background information. When tested on central emotional information, participants recalled more positive and negative central items than

neutral items. Also, participants remembered backgrounds that were paired with positive or negative items more poorly than backgrounds previously paired with neutral items. These findings suggest that emotional information attracts attention which strengthens memory for this information (see Edelman & Levine, 2010, for a review on emotion and memory).

Although a number of studies investigated the role of emotions on cognitive performance in a number of domains, surprisingly very few studies have investigated how emotions influence participants' arithmetic performance. This is very surprising because the role of emotions is often alluded to or mentioned in the arithmetic literature (e.g., Ashcraft & Rudig, 2012; Xolocotzin, 2017). Moreover, three lines of evidence suggest that emotions may importantly influence arithmetic performance. First, a number of studies found relations between mathematics anxiety and mathematical performance. Mathematics anxiety refers to "feelings of tension and anxiety that interferes with the manipulation of numbers and the solving of mathematical problem in a wide variety of ordinary life and academic situations" (Richardson & Suinn, 1972, p. 551). Previous research has found that correlations between mathematics anxiety and mathematical performance range between $-.28$ and $-.48$ (Hembree, 1990), such that people who score higher on math-anxiety scales have poorer performance than people who score much lower (see Dowker, Sarkar, & Looi, 2016, for a review). Findings suggest bi-directional relations between mathematics anxiety and mathematical performance (Carey, Devine, & Szucs, 2015). Indeed, (a) emotions generated by mathematics interfere with participants' performance (e.g., Young, Wu, & Menon, 2012) and (b) mathematics anxiety influences available resources during mathematical processing (e.g., Ashcraft & Kirk, 2001).

Second, Beilock and colleagues found that arithmetic performance decreased when individuals are tested under conditions of social pressures (Beilock & Carr, 2005; DeCaro, Rotar, Kendra, & Beilock, 2010). The desire for a high level of performance is thought to activate emotions that use up available resources and that, as a consequence, lead to lower performance. Such effects of choking under pressure are another line of evidence that suggests that emotions influence arithmetic.

Third, findings from Schimack and Derryberry (2005) also suggest that emotions may importantly influence arithmetic performance (see also Kleinsorge, 2007, 2009). Participants were presented a positive (e.g., a baby), negative (e.g., a shark), or neutral (e.g., a hairdryer) picture together with two simple arithmetic problems (e.g., $3 \times 5 < 2 \times 8$). They had to determine as quickly as possible which of the two products was larger while ignoring the picture. Most interestingly, they found that

participants were slower in the arithmetic task when either positive or negative pictures were displayed compared to neutral pictures. They found no significant differences between negative and positive pictures. These findings suggest that emotions could influence arithmetic processes. However, no specific analyses were conducted to determine which arithmetic processes were affected by emotions (e.g., did emotions influence harder problems more than easier problems?). Therefore, we aimed at determining which arithmetic processes are influenced by emotions.

To advance our understanding of how emotions affect arithmetic performance, we adopted a strategy perspective in the present study. A strategy is defined as "a procedure or a set of procedures for achieving a higher-level goal or task" (Lemaire & Reder, 1999, p. 365). In some domains or tasks, strategies used by participants can be investigated directly because it is possible to collect external behavioral evidence of strategies (i.e., when participants are counting on their fingers to find solutions to problems like $7 + 8$). However, in most cognitive tasks, no external behavioral evidence is available. In these tasks, strategies have to be investigated indirectly, and they are inferred from the patterns of participants' performance that arise as a function of the factors that define the stimulus set. This occurs in arithmetic when participants are given arithmetic problem verification tasks.

In arithmetic problem verification tasks, participants are asked to determine if equations such as $4 \times 13 = 52$ are true or false. On true problems such as $4 \times 17 = 68$, participants use calculation strategies (i.e., they encode the problem, calculate the correct solution, compare the calculated and proposed solutions, make a true/false decision, and press a button to respond). Usually, participants are faster and more accurate on easier true problems than on harder true problems because the calculation strategy is more quickly (and more accurately) executed on easier problems. On false problems such as $4 \times 12 = 47$, participants use different heuristics (i.e., non-calculation strategies). For a problem like $4 \times 12 = 47$, they use a fast parity-violation checking strategy. That is, they check whether the parity rule (i.e., to be true, a product must be even, if either of its multipliers is even; otherwise, it must be odd) is respected or violated. This strategy is faster than calculation strategies because it dispenses participants from calculating the correct answer before comparing it with the proposed answer and making a true/false decision. A number of studies found that participants are faster to reject false problems that violate the parity rule than to reject false problems that respect the parity rule (e.g., Lemaire & Fayol, 1995; Lemaire & Reder, 1999; Lochy, Seron, Delazer, & Butterworth, 2000).

In the present experiment, to determine whether emotion influences arithmetic performance, we asked participants

to accomplish an arithmetic problem verification task. Participants had to verify true easier or harder problems and false problems that violated or respected the parity rule. Before each problem, participants saw a positive, negative, or neutral picture. They had to decide whether each picture includes a person or not before verifying each problem. We compared participants' performance on true and false problems separately, as a function of positive, negative, and neutral pictures.

Two hypotheses were tested here, one concerning influence of emotions on strategy execution and the other on effects of emotions on strategy use. The hypothesis that emotions influence strategy execution predicts that problem-difficulty effects (i.e., differences in performance between true easier and true harder problems) will vary in magnitudes with emotional pictures. Increased problem-difficulty effects could be observed if participants are slower (and/or less accurate) on harder problems after processing positive or negative emotional pictures. This would suggest that emotions influence strategy execution. Decreased problem-difficulty effects (as seen if participants are faster on harder problems after emotional pictures) would suggest that emotions improve strategy execution.

The hypothesis that emotions influence strategy use predicts that effects of parity-violation (as seen in differences between performance on false parity-match and parity-mismatch problems) will vary in magnitudes with emotional pictures. Decreased effects of parity-violation could be seen if participants use the calculation strategy on both problems that violate and problems that respect the parity rule after processing emotional pictures. This would suggest that emotions influence strategy use and lead participants to use only one strategy, the calculation strategy. Finally, increased effects of parity-violation could occur if participants are slower to reject false, parity-violation problems after processing emotional pictures, which could happen if emotions impair only strategy execution.

At this stage, given the lack of previous studies on the role of emotions on strategies and arithmetic, it is impossible to predict whether positive or negative emotions will differentially change magnitudes of problem-difficulty and parity-violation effects.

Method

Participants

Twenty-four (21 males and 3 females) graduate students at French Air Force Academy participated in this experiment. Participants were 22.2 years ($SD = 1.1$) and had a mean

number of years of education of 16 years ($SD = 0.9$). All participants reported normal or corrected-to-normal vision. An informed consent was obtained from each participant prior to participation.

Stimuli for the Arithmetic Problem Verification Task

The stimuli were 144 multiplication problems presented in a standard form (i.e., $a \times b = c$), with the operands a and b being either single or double-digit numbers. Single-digit operands ranged from 3 to 9, whereas double-digit operands ranged from 12 to 82. The basic set of equations consisted of 72 unique multipliers. A third of problems included two-even operands, one-even operand, or zero-even operand. Two types of multiplication problems were presented: True or False problems. All true problems had the same operands as false problems and differed only in the value given as the proposed product. This value was the correct product of the two operands for true problems. Based on the size of carry, half the problems were easier problems and half were harder problems. Thus, easier problems had their product of units between 3 and 21 (carry-size: 0–2), and mean correct products of 214 ($SD = 101$; range = 93–392), and harder problems had product units between 24 and 72 (carry-size: 2–7) and mean correct products of 228 ($SD = 104$; range = 64–441).

Two types of false problems were tested: (a) *Parity-Match* (or mismatch) problems involved false answers with odd-even status that were the same as those of the correct products, (b) *Parity-Mismatch* (or mismatch) problems involved false answers with odd-even status that were different from those of correct products. All false problems were created by varying differences between correct and proposed products. Incorrect answers were off by ± 1 or ± 3 (for parity-mismatch problems) and ± 2 (for parity-match problems) from correct answers, all else being equal.

Based on previous findings in arithmetic (see Cohen-Kadosh & Dowker, 2015; Gilmore, Göbel, & Inglis, 2018, for overviews), we controlled the following factors: (a) size of differences between correct and proposed answers, (b) no double-digit operand had zero or five as unit digit, (c) no double-digit operand had the same unit and decade digits, (d) the size and side of operands were controlled, such that all problems had both a single digit and a double digit operand and that half the problems had the double-digit operand in the left position and half in the right position, (e) all problems with only one even operand had half of their even multiplicand in the right position and the other half in the left position, (f) none of the problems included zero, one, or five as a single-digit operand, and (g) two

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

Problems	Positive	Negative	Neutral
Emotional Valence			
False – Match	7.55 (7.13–8.34; 0.31)	2.07 (1.4–2.52; 0.34)	5.04 (4.77–5.31; 0.17)
False – Mismatch	7.53 (7.18–8.2; 0.30)	2.06 (1.52–2.5; 0.29)	5.03 (4.81–5.28; 0.15)
True Easier	7.53 (7.13–8.22; 0.31)	2.07 (1.31–2.54; 0.34)	5.03 (4.77–5.3; 0.17)
True Harder	7.54 (7.14–8.28; 0.30)	2.07 (1.45–2.52; 0.31)	5.04 (4.77–5.31; 0.15)
<i>F</i>	0.02 ($p = .99$)	0.41 ($p = .98$)	0.03 ($p = .99$)
Arousal Ratings			
False – Match	5.07 (3.01–7.27; 0.94)	6.07 (5.02–7.29; 0.72)	3.54 (2–5.14; 0.87)
False – Mismatch	4.78 (3.2–6.35; 0.79)	6.09 (4–7.16; 0.66)	3.71 (1.72–6.52; 1.01)
True Easier	4.84 (3.08–7.31; 0.98)	6.15 (5–7.26; 0.53)	3.73 (2.32–6.97; 1.03)
True Harder	4.99 (3–7.35; 1.14)	6.10 (4.53–7.35; 0.68)	3.68 (2.17–6.23; 1.05)
<i>F</i>	0.12 ($p = .95$)	0.30 ($p = .83$)	0.84 ($p = .48$)

271 was never used as single-digit operand to avoid discrepancy
272 in the number of odd (3, 7, 9) and even digits (4, 6, 8).

273 Stimuli for Emotional Pictures

274 Four hundred thirty-two pictures were selected from
275 International Affective Picture System (IAPS; Lang &
276 Bradley, 2007; Lang, Bradley, & Cuthbert, 2008), depicting
277 144 negative-events (e.g., mutilations), 144 positive-events
278 (e.g., smiling baby), and 144 neutral-events (e.g., neutral
279 faces). Sixty percent of the pictures contained a whole
280 person (i.e., showing face and body). To maximize differ-
281 ences in emotional valence, pictures with the highest and
282 lowest valence ratings were respectively selected as positive
283 and negative pictures. Then, we selected for each positive
284 and negative picture those with the highest arousal ratings
285 (see Table 1).

286 Procedure

287 The procedure is illustrated in Figure 1. Stimuli were
288 presented on a 800 × 600 resolution computer screen in
289 a 42-point Courier New Font. Problems were displayed
290 horizontally in the center of the screen in a standard
291 arithmetic format “ $a \times b = c$ ”. The symbols and numbers
292 were separated by spaces equal to the width of one charac-
293 ter. At the beginning of each trial, participants saw a blank
294 screen for 500 ms, followed by an asterisk (*) displayed in
295 the center of the screen for 400 ms. A picture was then dis-
296 played for 1,500 ms followed by a “Presence of a whole
297 Human or Not?” decision task that remained on the screen
298 until participants’ response. Participants were instructed to
299 press the “K” key on an AZERTY keyboard if the picture
300 included a whole human and the “D” key if not. Partici-
301 pants were equally fast and made no errors to judge the

presence/absence of a whole human for emotionally posi- 302
tive, negative, or neutral pictures ($F_s < 1$). 303

304 Following participants’ response, an asterisk was
305 displayed for 400 ms in the middle of the screen. Then,
306 an arithmetic equation was displayed. Participants were
307 instructed to press the “L” or “S” keys to indicate whether
308 the equation was true or false. The equation remained on
309 the screen until participants’ response. Participants were
310 instructed to use their left and right index fingers to
311 respond, and the assignment of response to buttons was
312 counterbalanced across subjects. Participants were encour-
313 aged to respond as quickly and as accurately as possible.
314 No particular strategies were mentioned. The E-prime soft-
315 ware controlled stimulus display, response recording, and
316 collected response times with 1-ms accuracy.

317 Each of the 144 problems was solved once following a
318 positive, a negative, or a neutral picture. Problems were
319 randomly presented to participants, with the constraints
320 that no more than four consecutive problems were of the
321 same type, and that no more than three images displayed
322 before each problem involved the same emotion.

323 Following five practice trials, participants saw four blocks
324 of 108 trials (including 54 true and 54 false problems). They
325 did not receive any feedback after a given trial.

326 Results

327 Participants’ mean latencies on emotional pictures were
328 analyzed with a within-design analysis of variance
329 (ANOVA), 3 (Emotion: negative, positive, or neutral
330 pictures). A significant effect of valence was observed,
331 $F(2, 46) = 7.56, p < 10^{-5}, MSE = 68,594, \eta^2_p = .25$. Pairwise
332 comparison tests revealed that participants were slower on
333 negative pictures (2,265 ms) than on positive (2,190 ms)

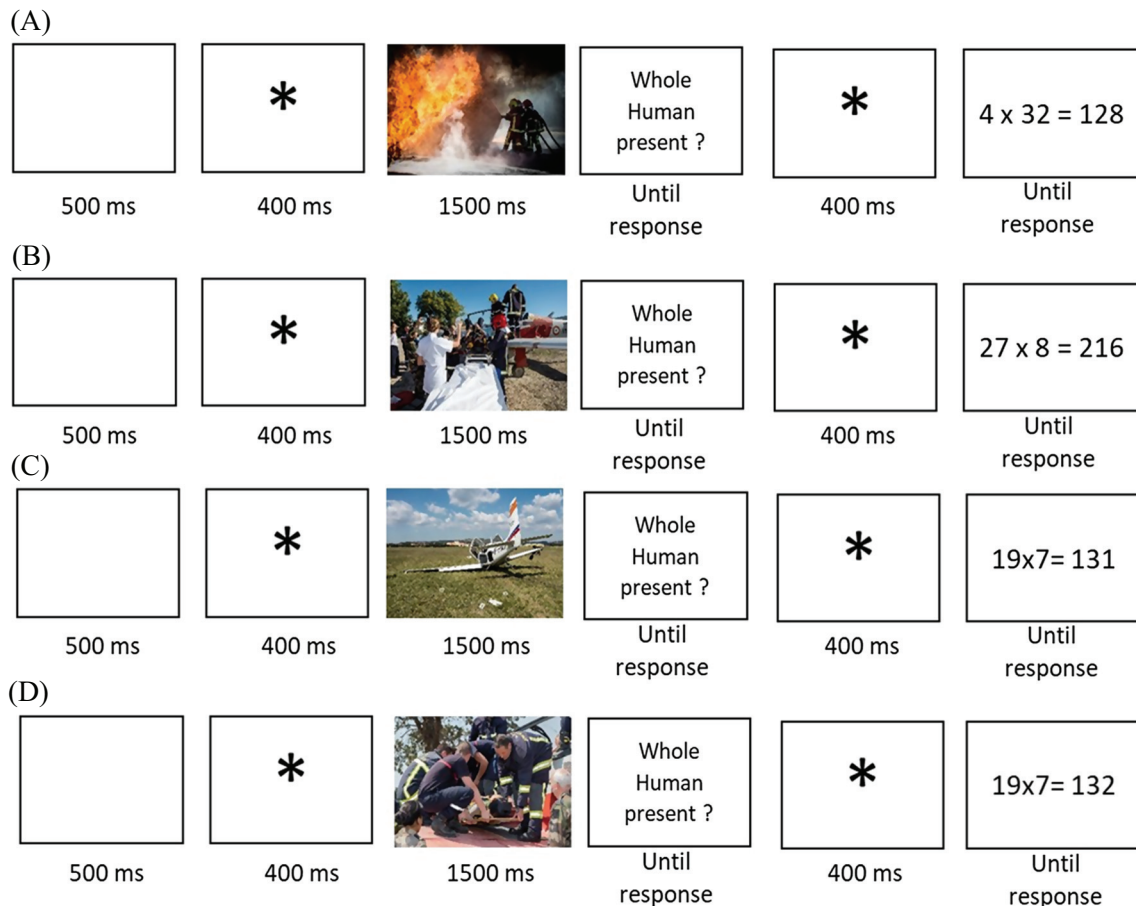


Figure 1. Sequence of events within an example trial. (A) Negative trial, True easier problem; (B) Negative trial, True harder problem; (C) Negative trial, False Parity-Match problem; (D) Negative trial, False Parity-Mismatch problem.

or on neutral pictures (2,221 ms) and on equally fast on positive and neutral pictures.

Effects of Emotions on True Problems Performance

Latencies on either true or false problems larger than the mean of the participant + 2.5 SDs (2.8%) were removed as well as all erroneously solved problems. Unless otherwise noted, differences were significant to at least $p < .05$. Participants' mean latencies and percentages of errors on true problems (Table 2) were analyzed with 2 (Problem Difficulty: easier, harder) \times 3 (Emotion: negative, positive, or neutral images) ANOVAs with repeated measures on each factor.

Participants were 1,034 ms faster [$F(1, 23) = 40.82$, $p < 10^{-5}$, $MSE = 342,000$, $\eta_p^2 = .69$] and made 5.5% fewer errors [$F(1, 23) = 71.36$, $p < 10^{-3}$, $MSE = 1,100$, $\eta_p^2 = .48$] on easier than on harder problems. The significant Problem Difficulty \times Emotion interaction [$F(2, 46) = 6.79$, $p < .01$, $MSE = 507,000$, $\eta_p^2 = .26$] resulted from variations in

magnitudes of problem difficulty as a function of emotional pictures. Effects of problem difficulty were larger on problems following neutral pictures [1,000 ms; $F(1, 23) = 32.58$, $p < 10^{-5}$, $MSE = 12,500,000$] than after negative images [834 ms; $F(1, 23) = 50.84$, $p < 10^{-5}$, $MSE = 8,770,000$]; they were the largest after positive pictures [1,266 ms; $F(1, 23) = 50.55$, $p < 10^{-6}$, $MSE = 19,800,000$]. This occurred because participants verified easier problems more quickly after processing a positive picture than after a neutral picture [-220 ms; $F(1, 23) = 5.27$, $p = .03$, $MSE = 446,931$] and were faster on harder problems after a negative than after a neutral picture [-266 ms; $F(1, 23) = 7.72$, $p < .01$, $MSE = 622,054$]. Participants were not influenced by negative pictures when solving easier problems or by positive pictures when solving harder problems ($F_s < 1.0$) compared to neutral pictures.

Effects of Emotions on False Problems Performance

Preliminary analyses revealed no differences in participants' performance between match and mismatch

Table 2. Mean latencies and percentage of errors (and *SDs*) on true easier and harder problems for negative, neutral, and positive emotions [Author: formatting ok?]

Emotions	Latencies (ms)			% Errors (<i>SD</i>)		
	Easier	Harder	Differences	Easier	Harder	Differences
Negative	2,598 (181.6)	3,432 (265.2)	834**	8.6 (1.0)	13.2 (1.6)	4.6
Neutral	2,698 (179.4)	3,698 (311.4)	1,000**	8.0 (1.1)	13.8 (2.3)	5.8
Positive	2,478 (184.9)	3,744 (312.9)	1,266**	7.7 (1.1)	13.9 (2.4)	6.2
Mean	2,591	3,625	1,034**	8.1	13.6	5.5**

Note. ** $p < .01$.

Table 3. Mean response latencies and percentages of errors (and *SDs*) on match and mismatch problems for negative, neutral, and positive emotions

Emotion	Latencies (ms)			% Errors (<i>SD</i>)		
	Match	Mismatch	Differences	Match	Mismatch	Differences
Negative	2,863 (237.4)	2,908 (251.7)	-45	10.8 (2.1)	3.2 (0.75)	7.6
Neutral	2,823 (240.9)	2,720 (224.4)	103*	11.7 (2.31)	4.3 (1.1)	7.4
Positive	3,025 (241.5)	2,675 (220.9)	350*	9.2 (1.8)	3.3 (1.5)	5.9
Mean	2,904	2,768	136*	10.6	3.6	7.0*

Note. * $p < .05$.

problems when problems included two odd operands and followed neutral images. This finding replicates previous findings of no parity-violation effects for problems with two odd operands (Krueger, 1986; Krueger & Hallford, 1984; Lemaire & Reder, 1999) and suggests that our participants accomplished our arithmetic problem verification task like in previous studies. To determine whether emotional valence of pictures modulate parity-violation checking strategy, mean response latencies and percentages of errors on false problems (Table 3) with two-even and one-even operand were analyzed with 2 (Parity: match, mismatch problems) \times 3 (Emotion: emotionally negative, emotionally positive, or neutral images) ANOVAs with repeated measures on each factor.

Parity effects were significant, as participants rejected mismatch problems more quickly [$F(1, 23) = 11.63, p < .01, MSE = 1,180; \eta^2_p = .36$] and more accurately [3.6% vs. 10.6%; $F(1, 23) = 21.94, p < 10^{-3}, MSE = 1,740; \eta^2_p = .49$] than match problems. Interestingly, the Emotion \times Parity interaction came out significant [$F(2, 46) = 11.63, p < .01, MSE = 1,180; \eta^2_p = .36$]. Planned comparisons showed that the parity effects were significant for neutral trials [103 ms; $F(1, 23) = 6.022, p = .02, MSE = 557,317$] and for positive trials [350 ms; $F(1, 23) = 22.74, p < 10^{-4}, MSE = 1,344,441$] but nonsignificant for negative trials (-45 ms; $F < 1.0$). Moreover, post hoc Newman-Keuls comparisons revealed that participants were 188 ms slower on mismatch problems following negative pictures relative to following neutral pictures and were 202 ms slower on match problems following positive pictures than after neutral pictures. In other words, participants' performance on false problems revealed decreased parity-violation effects from neutral to negative pictures (from 103 ms to

-45 ms) and increased parity-violation effects from neutral to positive pictures (from 103 ms to 350 ms).

Complementary Analyses of Emotional Intensity and Arousal on Performance

As can be seen from Table 1, picture selection based on maximizing differences in emotional valence led to arousal ratings being slightly higher for negative than for positive pictures. This raises the possibility that our differences between positive and negative emotions on true and false problems performance might be driven by arousal ratings. To determine whether arousal drove our findings, participants' performance was analyzed for a subset of our stimuli that were matched on arousal ratings. To obtain sets of negative and positive pictures with comparable arousal ratings, 20 negative and 20 positive pictures respectively with a valence rating < 2.52 and > 7.13 were selected for each problem type. Negative pictures had mean valence ratings of 2.13 ($SD = 0.29$) and mean arousal ratings of 5.79 ($SD = 0.54$). Positive pictures had mean valence ratings of 7.58 ($SD = 0.31$) and mean arousal ratings of 5.5 ($SD = 0.65$). Differences between arousal ratings were not significant [$F(1, 19) = 1.62, p > .2$]. We found the same effects (see means in Table 4). The significant Problem Difficulty \times Emotion interaction [$F(2, 46) = 6.17, p < .01, \eta^2_p = .21$] resulted from variations in magnitudes of problem difficulty as a function of emotional pictures. Also, the Emotion \times Parity significant interaction [$F(2, 46) = 7.74, p < 10^{-3}, \eta^2_p = .25$] revealed significant match-mismatch differences in the control and positive conditions and lack of match-mismatch differences in the negative condition.

Table 4. Mean response latencies (and *SDs*) on match and mismatch problems and easier and harder problems for negative, neutral, and positive emotions

Emotions	Match	Mismatch	Differences	Easier	Harder	Differences
Negative	2,995 (233.9)	3,020 (248.5)	−25	2,543 (162.7)	3,445 (248.5)	902*
Neutral	2,846 (213.4)	2,630 (213.4)	216*	2,634 (169.6)	3,665 (288.1)	1,031*
Positive	2,980 (203.4)	2,598 (203.4)	382*	2,441 (184.8)	3,724 (294.4)	1,283*
Mean	2,940	2,749	191*	2,539	3,611	1,072*

Note. * $p < .05$.

These findings are exactly like those in the analyses on the whole set of problems.

Discussion

The goal of the present study was to test the influence of emotions on arithmetic performance. Participants were asked to verify true and false arithmetic problems. Each problem was preceded by an emotionally positive, negative, or neutral picture. Effects of emotions on participants' performance were observed while verifying true and false problems. On true problems, emotions changed magnitudes of problem difficulty effects (i.e., better performance on easier than on harder problems). Relative to problem difficulty effects found after processing neutral pictures, decreased problem difficulty effects were seen after negative pictures and increased difficulty effects were observed after positive pictures. This occurred because participants were faster while verifying harder problems following negative emotions and while verifying easier problems following positive emotions.

Given previously found distracting effects of negative emotions in several experimental contexts, as seen in poorer performance (Carretié, 2014), and given how math anxiety correlates negatively with participants' performance (Dowker et al., 2016), negative emotions could be expected to lead participants to poorer arithmetic performance, especially on harder problems. Actually, we found the reverse. Participants' solved arithmetic problems faster after processing negative pictures. Note that increased performance under negative emotions performance is not specific to the present experimental context. It has been found in several previous studies. For example, Blanchette and colleagues (e.g., Blanchette & Campbell, 2012, Blanchette & Caparos, 2013) found that when participants were asked to reason about personally relevant emotional experiences (e.g., sexual abuse, war, terrorist attacks), emotions led to increased reasoning performance. This does not mean that negative emotions always have positive effects on

participants' performance, as many previous studies in a variety of cognitive domains (including in reasoning; e.g., Blanchette & Richards, 2004) found negative effects of emotions on participants' performance. In fact, many researchers acknowledge that emotional stimuli can have positive or negative effects on participants' performance. To cite just one recent example, Figueira et al. (2017, p. 984) wrote "Emotional stimuli can influence cognition through beneficial or detrimental effects (e.g., enhanced processing of goal-relevant emotional stimuli or increased distraction due to goal-irrelevant emotional stimuli)".

One potential reason for participants to increase their speed after processing negative pictures here is that they tried to neutralize negative emotions by quickly switching from processing negative pictures to the arithmetic task and focused their attention on solving problems. This was most beneficial on harder problems. In our arithmetic experiment, participants may have increased their speed by engaging in the arithmetic task after processing negative pictures in order to more quickly disengage from negative unpleasant experience triggered by negative emotions. This was most efficient on the harder problems, as there is more room for improvement on those problems than on easier problems. In other words, participants may have strategically regulated their negative emotions using emotional disengagement strategies after the picture task to redeploy their attentional resources to the arithmetic problem-solving task. Such an emotional regulation strategy efficiently neutralizes potential deleterious impacts of negative emotions.¹

In contrast to negative pictures, positive pictures led participants to be slower while verifying arithmetic problems. One possible explanation is that participants were still processing positive emotion pictures while encoding and solving arithmetic problems. Such continued emotional processing interfered with arithmetic processes executed to verify arithmetic problems and, as a consequence, increased solution latencies. In other words, it is possible that positive emotions temporarily distracted participants from focusing on the arithmetic problem verification task. Such interference (or distracting) effects of positive

¹ We performed participant-based correlations between latencies in the picture and arithmetic tasks, separately for each emotional condition. All correlations were positive. This is inconsistent with the hypothesis that participants adopted an emotional regulation strategy during picture processing, and not while encoding and solving arithmetic problems [Author: Please integrate footnote into the main body, if possible].

emotions found here while verifying true problems after positive pictures may be a specific manifestation of general distracting effects of emotions on cognitive performance already found in many cognitive domains, like attention, perception, visual processing, or inhibition. For example, Rowe, Hirsh, and Anderson (2007) found that positive emotions increased interference effects in a Simon task because positive emotions distracted people and increased their latencies, especially on incongruent items.

Most importantly, because many previous studies in arithmetic showed that participants solve true easier and harder problems with calculation strategy, the present findings suggest that negative emotions increased speed of strategy execution whereas positive emotions slowed down strategy execution while participants verified arithmetic problems. In other words, the present findings suggest that emotions influence how participants execute strategies when they use the same strategy to accomplish cognitive tasks.

Emotions did not only modulate participants' performance on true problems performance; they also influenced participants' performance on false problems. Effects of emotions on participants' performance while verifying false problems were seen in variations of parity-violation effects (i.e., better performance on problems for which parity of proposed and correct answers matched than on problems for which parity mismatched). Relative to parity-violation effects found after processing neutral pictures, increased parity-violation effects were found after positive pictures, and no significant parity-violation effects were seen after processing negative pictures.

Parity-violation effects disappeared in negative-picture condition because participants did not use the fast parity-violation checking strategy on parity-mismatch problems. Negative emotions led them to use the slower calculation strategy. It seems that negative emotions prevented them from analyzing problem features to detect that parity of the proposed and correct answers are different. This led them to use the default, slower calculation strategy. In contrast, positive pictures did not lead participants to use calculation strategy on parity-mismatch problems. Positive emotions did not prevent them from noticing that parity of proposed and correct answers is different, and from using this difference to quickly reject false, parity-mismatch problems. On parity-match problems, participants most likely used the calculation strategy, but executed it more slowly. One possibility is that participants were distracted following positive pictures, which led them to execute the calculation strategy more slowly, exactly like they did on true problems that they solved using a calculation strategy.

Most importantly, as many previous studies in arithmetic (e.g., Anders, Hinault, & Lemaire, 2018) found, parity-violation effects result from differences in strategy use (i.e., participants use a slow, calculation strategy to verify

parity-match problems and a fast parity-violation strategy on parity-mismatch problems); changes of magnitude in parity-violation effects as a function of emotional pictures, found here, suggest that emotions influence arithmetic performance via strategy use. More specifically, different emotions lead participants to use different strategies to solve arithmetic problems.

In conclusion, the present findings suggest that emotions influence arithmetic performance via strategy use and strategy execution. One potential limitation of the present study is that it is impossible to disentangle when emotions influence strategy use, strategy execution, or both. In a problem-verification task, problem-difficulty on true problems and parity-violation effects on false problems are the result of strategy execution and strategy use, respectively. However, because each of these effects is an indirect evidence of strategy execution and strategy use, it is impossible to determine whether emotions change both strategy use and strategy execution, or only one of them. To determine this, future studies may use the choice/no-choice method proposed by Siegler and Lemaire (1997) that assess strategy use and strategy execution independently. Future studies should also use tasks in which it is possible to collect external behavioral evidence of which strategy participants use on each problem (e.g., arithmetic problem production tasks combined with verbal protocols). Such an approach may greatly help us further understand how emotions influence arithmetic performance.

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