Journal of
Cognitive Neuroscience

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Journal:	*Journal of Cognitive Neuroscience*
Manuscript ID	Draft
Manuscript Type:	Original
Date Submitted by the Author:	n/a
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Keywords:	Emotion, Numerical processing, Neuroimaging

How negative emotions influence arithmetic performance: A magnetoencephalography study.

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Abstract

In this study, we used magnetoencephalography (MEG) and adopted a strategy approach to determine how negative emotions influence arithmetic performance. Participants had to find estimates of two-digit multiplication problems, while their strategies were monitored for each problem. Problems were displayed superimposed on emotionally negative or neutral pictures. Behavioral results showed that negative emotions influenced arithmetic performance, especially while executing the harder strategy. MEG data showed decreased activations under negative emotions in brain regions known to specifically underlie arithmetic neural processes, and no effects of emotions in regions involved in domain-general mechanisms. Interestingly, decreased activations occurred very early after the onset of the arithmetic problems and were not found in later time windows. These results suggest that negative emotions impair the early domain-specific processes (such as encoding arithmetic problems), possibly as a result of competing resources between emotional and arithmetic processing. These findings have important implications for further our understanding of neural and cognitive mechanisms underlying effects of negative emotions in arithmetic and for further investigating how emotions influence cognition.

Introduction

How do negative emotions influence cognition in general and specific cognitive domains, like arithmetic, in particular? Although it has long been known that emotions influence both domain-general (e.g., memory, attention, reasoning, decision making) and domain-specific (e.g., spatial, arithmetic, language processing) cognitive activities (see Lemaire, 2022; Robinson et al., 2013, for overviews), unknown are via which mechanisms negative emotions impair cognitive performance. To further our understanding of emotion-cognition in arithmetic, we investigated the spatial-temporal dynamics of brain activations with magnetoencephalography (MEG) data while participants solved complex arithmetic problems under negative and neutral emotions. The data document differences in which and when brain areas are activated under negative and neutral emotions. Before outlining the logic of the present study, we first briefly review previous findings on emotion-cognition relations and the neural bases of deleterious effects of negative emotions on cognition. Then, we review prior findings on effects of negative emotions on arithmetic performance.

Neural bases of emotion-cognition relations

Numerous studies examined how emotions influence cognition in a wide variety of cognitive domains such as attention, memory, judgment, decision-making, or reasoning (see Lemaire, 2022; Robinson et al., 2013, for reviews). Emotions sometimes enhance and sometimes impair cognitive performance. Emotions lead to improved performance when they are relevant to successfully complete the target task or when they are relevant to participants' past emotional experience. For example, Blanchette and Campbell (2012) found better reasoning performance when war veterans reasoned on war statements than on neutral statements. As another example, Talamini and colleagues (2021) showed improved pictures recognition when these pictures were emotionally congruent with music they had heard before, compared to emotionally incongruent or neutral pictures. In contrast, when they are not relevant to the task or to participants' past emotional experience, emotions impair cognitive performance. For examples, participants performed more poorly on Stroop tasks when asked to name the color of the ink of emotional words relative to neutral words (e.g., Straub et al., 2022); they obtained poorer recall or recognition performance under stress in episodic memory tasks (e.g., Davis et al., 2019), or they reasoned more poorly on statements preceded by an irrelevant emotional picture (e.g., Blanchette, Gavigan, & Johnston, 2014). Researchers proposed that effects of emotions on cognitive performance occur via attentional capture mechanisms (Okon-Singer et al., 2015; Pessoa, 2009; Verbruggen & De Houwer, 2007). According to this attentional capture hypothesis, emotions would automatically grab participants' exogeneous attention. Such attentional capture helps participants focus on the task or target stimuli when emotions are relevant to task success, but distracts participants away from the target cognitive task, leading them to perform more poorly under emotional states, when emotions are not relevant to the task.

Brain-imaging studies have helped further our understanding of neural bases for how emotions influence cognition. fMRI studies have shown attentional resource-independent automatic activation of an affective system, including for example the amygdala, or prefrontal regions (e.g., ventrolateral prefrontal cortex, ventromedial prefrontal cortex, and orbitofrontal cortex), during the processing of emotionally negative stimuli (e.g., Aldhafeeri et al., 2012; Vuilleumier et al., 2001; Whalen et al., 1998). In addition, EEG studies have shown that the Late Positive Potential (LPP), a centro-parietal event-related potential reflecting the maintenance of attentional resources on salient stimuli, exhibits increased amplitude during the processing of negative stimuli (compared to positive or neutral stimuli). Such increased amplitude continues over time even after emotional stimuli have disappeared (e.g., Cuthbert et al., 2000; Hajcak, Dunning, & Foti, 2009; Hajcak & Olvet., 2008; Werheid et al., 2005). Together, these neuroimaging data suggest that emotional processing has privileged access to attentional and cognitive resources, which may be deleterious to performance on cognitive tasks in which emotions are irrelevant. This has been found in attention (e.g., Hartikainen, Ogawa, & Knight, 2000; Wang et al., 2005; Yamasaki, LaBar, & McCarthy, 2002), and memory (e.g., Denkova et al., 2010; Dolcos et al., 2007, 2008; Dolcos & McCarthy, 2006; Iordan & Dolcos, 2017; see Iordan, Dolcos, & Dolcos, 2013, for a review). For example, in a fMRI study investigating the neural bases of deleterious effects of emotions on memory performance, Dolcos and McCarthy (2006) asked participants to encode three human faces and then to perform a face recognition task after an 11-sec. delay. During this delay, participants saw scrambled, emotional, or neutral task-irrelevant pictures. Participants had poorer working-memory performance when pictures were emotionally negative compared to neutral or scrambled pictures. At the neural level, the authors showed an interaction between an affective ventral system composed mainly of the amygdala, the orbitofrontal cortex, the ventrolateral prefrontal cortex, and the occipitotemporal cortex, on the one hand, and a cognitive/executive dorsal system including the dorsolateral prefrontal cortex, the lateral parietal cortex, and the medial temporal lobe memory system, on the other hand. More specifically, during the short delay, negative emotions stimuli triggered a hyperactivation of the ventral affective system accompanied by a deactivation of the dorsal cognitive system that could lead to the disturbance of working memory mechanisms by irrelevant negative stimuli.

Decreased activations of brain regions crucial for target cognitive tasks together with increased activations of affective systems and decreased performance have mainly been shown in working memory (see Iordan et al., 2013, for a review), although a few studies have reported similar results in attention (e.g., Moore et al., 2019; Shafer et al., 2012). As hypothesized by several authors, it may hold across many cognitive activities (Iordan et al., 2013). The issue is whether this interplay of emotional and cognitive neural systems underlying decreased performance under emotions holds for domain-general cognitive functions, such as working memory and attention, or whether it also holds for domain-specific activities (e.g., arithmetic, spatial, or music cognition). We address this issue in the present study that focuses on arithmetic and that aimed at determining whether decreased arithmetic performance under irrelevant emotions is associated with hyperactivations of the emotional neural systems combined with hypoactivations of target brain regions or networks known to be crucially involved in arithmetic problem solving.

Neural bases of emotion-arithmetic relations

Behavioral studies on effects of emotions on arithmetic performance showed that both negative and positive emotions affect performance while participants solve arithmetic problems (Fabre & Lemaire, 2019; Framorando & Gendolla, 2018, 2019; Kleinsorge, 2007, 2009; Lemaire, 2022, 2024; Lallement & Lemaire, 2021, 2023; Liu et al., 2021; Schimmack, 2005; Zhu et al., 2021, 2022). These studies found that, like in other cognitive domains, irrelevant negative emotions impair participants' arithmetic performance. For example, Lallement and Lemaire (2021) asked participants to verify simple one-digit addition problems (e.g., 8 + 4 = 13. True? False?), or to estimate the products of complex two-digit multiplication problems (e.g., which estimate between 3200 and 4500 is closer to the correct product of 42 × 84?). Problems were displayed superimposed on emotionally negative or neutral pictures. Participants were slower to solve both simple and complex arithmetic problems in the emotionally negative condition than in the neutral condition. As in other cognitive domains, such deleterious effects of irrelevant negative emotions on arithmetic performance have been explained by the attentional capture hypothesis. According to this hypothesis, emotions capture part of the participants' attention, which would prevent them from processing the target cognitive task optimally and/or delay them from engaging in the arithmetic task.

Neuroimaging studies of arithmetic processing found that solving arithmetic problems involves a large brain network (see Arsalidou & Taylor, 2011; Menon, 2015; Peters & De

Smedt, 2018, for reviews), including prefrontal regions (e.g., dorsolateral prefrontal cortex, ventrolateral prefrontal cortex) as well as parietal regions (e.g., intraparietal sulcus, superior parietal lobule, angular gyrus). Arithmetic processing is thought to involve both domain-general mechanisms (like working memory, attentional processes, inhibitory control) and domain-specific mechanisms (e.g., processing operand magnitudes, operation symbols, carry over). It has been assumed that activations of prefrontal regions may be triggered by domain-general processes and that activations of parietal regions may support domain-specific processes in arithmetic (see Arsalidou & Taylor, 2011; Dehaene et al., 2003; Menon, 2015; Peters & De Smedt, 2018, for reviews).

Given that neural correlates of deleterious effects of negative emotions on arithmetic performance have never been investigated, the present study aimed at determining whether activations of brain networks subserving arithmetic performance are modulated by emotions. Previous data on neural activations in individuals with high levels of mathematics anxiety suggest that cerebral activations during arithmetic problem solving are modulated by negative emotions (see Artemenko, Daroczy, & Nuerk, 2015; Moura-Silva, Torres Neto, & Gonçalves, 2020; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2016, for reviews). Mathematics anxiety refers to feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of problems in a wide variety of ordinary life and academic situations (Richardson & Suinn, 1972). It is associated with decreased arithmetic performance (see Barroso et al., 2021; Dowker, Sarkar, & Looi, 2016; Mammarella, Caviola, & Dowker, 2019, for reviews). Thus, increased activations of fear network (involving the amygdala) and pain network (involving the insula) combined with decreased activities in brain regions known to underlie arithmetic processing (e.g., dorsolateral prefrontal cortex; posterior parietal cortex) were found in high math-anxious individuals compared to low-math anxious individuals (e.g., Klados et al., 2019; Lyons & Beilock, 2012; Young, Wu, & Menon, 2012). Note however that studies on the neural bases of mathematics anxiety provide only indirect correlational evidence of the modulation of the neural bases of arithmetic by emotions. This prevents from knowing which of the crucial arithmetic and non-arithmetic processes are influenced by emotions, and when these processes are influenced by emotions. The present study determines whether negative emotions triggered by external stimuli modulate the neural bases of arithmetic and can lead to decreased arithmetic performance.

In sum, previous studies on emotion-cognition relations found that emotions lead to decreased cognitive performance when they are not relevant to the task. The same results have been found in the field of arithmetic and have been explained by a mechanism of attentional capture by emotions leading participants to be distracted away from the target task. Neuroimaging studies in attention and memory have investigated the neural bases of this emotional distractibility and have shown hyperactivation of the affective system accompanied by deactivation of the cognitive system involved in the target tasks. The present study, by deciphering brain activations and their time course was expected to help determine (a) whether decreased performance under negative emotions is also associated with hyperactivation of the affective system and deactivation of the cognitive system, like in other cognitive domains, and (b) which of the cognitive mechanisms (e.g., peripheral encoding and responding vs. central calculation) crucial for arithmetic are influenced by negative emotions.

Overview of the present study

The present study aimed at determining (a) how negative emotions influence arithmetic processing and (b) which mechanisms of target cognitive tasks are influenced by emotions and when this influence occur. We adopted a strategy approach to address these issues and used a within-trial emotion induction procedure while participants solved arithmetic problems. We collected both behavioral performance and MEG data and manipulated the type of strategies participants had to execute on each problem.

Our approach was fruitful in many respects. First, by adopting a strategy perspective and asking participants to execute a given strategy on all problems of a given set and another strategy on another matched set of problems, effects of emotions on performance and brain activations were not contaminated by strategic variations (e.g., participants would use a given strategy more often on easier problems and a different strategy on harder problems; different participants would use different numbers and sets of strategies). Second, our approach enabled us to go beyond general account of deleterious effects of negative emotions in terms of general processing mechanisms, such as attentional capture. Indeed, we could determine how and when emotions grab exogenous attention and distract participants away from the target cognitive task. Our approach was also expected to help us know whether emotions affect domain-general mechanisms (e.g., attentional control), task/domain-specific mechanisms (e.g., encoding of the problem, calculation, retrieval of the result in long-term memory, decision making, responding), or both types of mechanisms. Finally, MEG data enabled us to compare the spatial-temporal dynamics of brain activations under emotionally neutral or negative conditions.

We asked participants to estimate the results of two-digit multiplication problems (e.g., 64 x 52) displayed superimposed on emotionally negative or neutral pictures. They were instructed to accomplish this task by executing the required strategy among two computational estimation strategies. Since a wide variety of strategies are known to be spontaneously used by participants when they solve arithmetic problems (e.g., Siegler, 2007), the great advantage of imposing strategies is to fully control how participants perform the task to ensure that they all perform it the same way, and that behavioral and brain data are not contaminated by differences in which strategies they use to solve a set of problems, how often participants use available strategies, how they select and execute these strategies.

We tested several hypotheses regarding (a) how negative emotions influence arithmetic processing (i.e., they delay triggering and execution of arithmetic processes vs. they do not change onset of processes but impair how efficiently mechanisms are executed), (b) which mechanisms (i.e., domain-general and/or domain-specific mechanisms) are influenced by emotions, and (c) which processing steps within strategies used by participants are specifically or not specifically influenced by emotions during arithmetic tasks.

Concerning how negative emotions influence arithmetic processing, we tested the three following alternative hypotheses. First, emotions momentarily interrupt and therefore delay the triggering and execution of key mechanisms while solving arithmetic problems, without impairing the quality of this execution, as assumed by the freezing hypothesis proposed by Verbruggen and De Houwer (2007). In other words, emotions would lead participants to first process irrelevant emotional information before focusing on target arithmetic problem-solving task. Once attention is disengaged from and inhibits emotional processing, it is fully re-engaged in arithmetic processing, and participants execute all underlying arithmetic mechanisms without being disturbed by negative emotions. This delayed arithmetic processing hypothesis predicts that brain areas known to be specifically activated during arithmetic problem solving (the dorsolateral and ventrolateral prefrontal cortex, anterior cingulate, angular gyrus, supramarginal gyri, intra-parietal sulcus, fusiform gyrus, and hippocampus) would be activated later in the emotionally negative condition than in the emotionally neutral condition. Second, emotions do not interrupt execution onset of key arithmetic mechanisms but impair efficient execution of these mechanisms. This could occur if emotional and arithmetic processing compete for attentional resources while solving arithmetic problems, as assumed by the dual competition framework proposed by Pessoa (2009). That is, following emotion induction, participants would not disengage from and inhibit emotional processing. They would share their attentional resources between emotional and arithmetic processing leading to fewer resources available for the target arithmetic processing task. Consequently, participants would execute the series of arithmetic processing steps less efficiently. This shared-attentional resource hypothesis predicts similar time courses of activation of brain areas known to support arithmetic processing in emotionally neutral and negative conditions, but lower activations of these brain areas in the emotionally negative condition. Third, emotions could exert their deleterious effects both on onset of arithmetic processes and on the quality of their execution. This would be seen in both delayed triggering and execution of mechanisms involved in the arithmetic task and by competition of resources between emotional and arithmetic processing. This could occur if participants do not fully disengage from and inhibit emotional processing once engaged in the arithmetic problem-solving task. This hypothesis predicts both lower activations and later activations of brain networks supporting arithmetic processing in the emotionally negative condition compared to the neutral condition.

The second set of hypotheses under test here concerns which mechanisms (i.e., domain-general or domain-specific) are influenced by negative emotions. First, emotions could only exert their influence on domain-general mechanisms involved in arithmetic (e.g., attentional processes, maintenance of information in working memory, inhibitory control). This hypothesis predicts differences in activations of brain regions involved in general cognitive functions in arithmetic (ventrolateral and dorsolateral prefrontal regions) between negative and neutral conditions, with a lower and/or later activation of these brain regions in the emotionally negative condition compared to the neutral condition, and no differences in activations of brain regions specifically involved in arithmetic (i.e., posterior superior parietal lobe, fusiform gyrus, intraparietal sulcus, supramarginal gyrus, and angular gyrus). Alternatively, emotions could influence domain-specific mechanisms (e.g., problem encoding, calculation or retrieval of the result in memory) during arithmetic problem solving. This hypothesis predicts differences in activations of brain regions specifically involved in arithmetic problem solving between emotionally negative and neutral conditions (i.e., posterior superior parietal lobe, fusiform gyrus, intraparietal sulcus, supramarginal gyrus, and angular gyrus), and no differences in activations of brain regions involved in general cognitive functions in arithmetic (e.g., ventrolateral and dorsolateral prefrontal regions). Finally, emotions could influence both domain-general and domain-specific mechanisms. This hypothesis predicts differences in activations (in amplitude or time course) of brain regions involved in general cognitive functions in arithmetic (ventrolateral and dorsolateral prefrontal regions) as well as occipito-temporal and parietal regions specifically involved in arithmetic (i.e., posterior superior parietal lobe, fusiform gyrus, intraparietal sulcus, supramarginal gyrus, and angular gyrus) between emotionally negative and neutral conditions.

The third hypothesis tested in the present study concerns which processing steps within strategies used by participants are specifically or not specifically influenced by emotions during arithmetic tasks. Using the MEG technique, we should be able to determine precisely which processing step(s) emotions affect while participants solve arithmetic problems. Thus, we should observe differences in brain activations between negative and neutral conditions at 0-200 ms after the display of arithmetic problems if emotions influence the encoding mechanisms, at 300-500 ms if emotions influence the retrieval of results in memory, at 500-3000 ms if emotions influence calculation processes, and even later if emotions influence the response stage.

Method

Participants

Forty-eight right-handed participants (*mean* age: 21.8 y.o.; age range: 18—30 y.o.) took part in this experiment (see Table 1 for participants' characteristics). They were paid 10 euros per hour for their participation. Informed consents were obtained from participants before the beginning of the experiment. This study was approved by the National Ethics Committee in France (Ref #: SI CNRIPH 20.04.02.47414).

Table 1. Participants' characteristics.

Characteristics	
N (men)	48 (10)
Mean age in y.o. (*SDs*)	21.8 (3.2)
Mean number of years of formal education (*SDs*)	15.1 (1.8)
MHVS *(SDs)*	18.3 (3.9)
Arithmetic fluency *(SDs)*	35.9 (13.7)
General anxiety *(SDs)*	43.8 (9.9)
Mathematics anxiety *(SDs)*	59.2 (17.3)

Note. MHVS: French version of the Mill-Hill Vocabulary Scale (Deltour, 1993; Raven, 1958). MHVS consists of 34 items distributed across three pages. Each item included a target word followed by six proposed words, and the task consisted in identifying which word was the closest to the target. Arithmetic fluency: Scores obtained in a paper-and-pencil arithmetic test (French et al., 1963) in which participants had to solve as many addition, subtraction, and multiplication problems as possible in six minutes. General anxiety: Scores obtained on a 20-item self-report questionnaire assessing participants' general anxiety level (STAI, Spielberger, 1983). Mathematics anxiety: Scores obtained on a 25-item questionnaire in which participants indicated, using self-report scales, how anxious they feel in various mathematics-related situations (sMARS, Alexander & Martray, 1989).

Following previous studies on emotion and arithmetic (e.g., Fabre & Lemaire, 2019; Lallement & Lemaire, 2021), where effect size of emotion on arithmetic performance ranged from .35 to .50, we used a η^2p = .40 to determine sample size using an *a-priori* power analysis (G*Power; Faul et al., 2007). Using a η^2p =.40, our study design involving two repeated factors (strategy and emotion) could achieve 95% power with 28 participants. In order to exceed this criterion and achieve greater than 95% power, we recruited 48 participants.

Stimuli

Multiplication problems. The stimuli were two sets of 96 multiplication problems presented in a standard form (i.e., *a* x *b*) with the operands *a* and *b* being two-digit numbers (e.g., 64 x 52; see Table 2 for the list of multiplication problems). One set was composed of multiplication problems for which the rounding-down strategy, RD (i.e., rounding both operands down to their nearest decades) was the better strategy to estimate the products (e.g., 64 x 52). It was the better strategy because it yielded the closest product estimates from correct products. The other set included problems for which the rounding-up strategy, RU (i.e., rounding both operands up to their nearest decades) was the better strategy (e.g., 59 x 26). Within each set, half the problems were presented together with emotionally neutral pictures (e.g., *mushrooms*) and half with emotionally negative pictures (e.g., *a corpse*). Moreover, half the problems were homogeneous problems, and half were heterogeneous problems. Both operands had their unit digits smaller than 5 (e.g., 64 x 52) in half the homogeneous problems and larger than 5 (e.g., 59 x 26) in the other homogeneous problems. The unit digit was smaller than 5 in the first operand and larger than 5 in the second operand (e.g., 31 x 56) for half the heterogeneous problems; the reverse was true in the other heterogeneous problems (e.g., 67 x 41). Moreover, the problems of different categories (i.e., RD / RU problems x Neutral / Negative conditions) were matched on (a) the side of the larger operand (i.e., half the problems of each category had their largest operand on the left position and half on the right position),

(b) the size of the correct products, and (c) the mean percentage deviations between correct products and estimates (calculated with the following formula: ([(estimate – correct product)/correct product] x 100). Given previous findings in arithmetic (see Cohen Kadosh & Dowker, 2015; Gilmore, Göbel, & Inglis, 2018; Knops, 2019, for overviews), we controlled the following factors: (a) no operands had 0 or 5 as unit digits; (b) digits were not repeated in the same decade or unit positions across operands (e.g., 43 x 49); (c) no digits were repeated within operands (e.g., 44 x 58); (d) no tie problems (e.g., 32 x 32) were used; and (e) operands were between 21 and 89.

Table 2. List of multiplication problems

RD Problems				RU Problems			
Homogeneous Problems		Heterogeneous Problems		Homogeneous Problems		Heterogeneous Problems	
23 x 61	54 x 83	31 x 56	56 x 41	26 x 59	57 x 68	29 x 64	59 x 73
23 x 64	61 x 23	31 x 67	56 x 82	26 x 87	57 x 86	29 x 73	59 x 74
24 x 61	61 x 24	31 x 68	57 x 42	26 x 89	58 x 46	29 x 74	62 x 39
24 x 63	61 x 54	31 x 78	61 x 47	27 x 59	58 x 67	29 x 84	62 x 59
24 x 83	62 x 34	32 x 76	62 x 79	27 x 86	58 x 76	38 x 74	63 x 39
32 x 64	62 x 54	32 x 86	67 x 31	28 x 56	59 x 26	39 x 54	63 x 49
32 x 74	63 x 24	41 x 56	67 x 41	28 x 76	59 x 27	39 x 62	63 x 59
34 x 52	63 x 42	41 x 67	67 x 52	28 x 86	59 x 46	39 x 63	64 x 29
34 x 62	63 x 74	41 x 68	68 x 31	36 x 78	67 x 58	39 x 64	64 x 39
34 x 82	64 x 23	41 x 76	68 x 41	36 x 79	68 x 37	39 x 74	64 x 57
42 x 63	64 x 32	41 x 87	71 x 46	36 x 89	68 x 57	39 x 84	64 x 58
42 x 83	64 x 52	42 x 57	72 x 46	37 x 68	76 x 28	43 x 69	69 x 43
43 x 52	64 x 52	46 x 51	76 x 32	38 x 46	76 x 38	48 x 53	69 x 53
43 x 74	64 x 53	46 x 71	76 x 41	38 x 76	76 x 58	49 x 63	69 x 54
52 x 34	73 x 54	46 x 72	76 x 53	39 x 47	78 x 36	49 x 83	73 x 29
52 x 43	74 x 32	47 x 61	78 x 31	46 x 38	79 x 36	53 x 48	73 x 59
52 x 64	74 x 43	51 x 46	78 x 51	46 x 58	79 x 46	53 x 69	74 x 29
52 x 64	74 x 53	51 x 78	79 x 62	46 x 59	86 x 27	54 x 39	74 x 38
53 x 64	74 x 63	51 x 86	82 x 56	46 x 79	86 x 28	54 x 69	74 x 39
53 x 74	82 x 34	52 x 67	86 x 32	47 x 39	86 x 57	54 x 79	74 x 59
53 x 84	83 x 24	52 x 86	86 x 51	47 x 56	87 x 26	57 x 64	79 x 54
54 x 61	83 x 42	52 x 87	86 x 52	56 x 28	89 x 26	58 x 64	83 x 49
54 x 62	83 x 54	53 x 76	87 x 41	56 x 47	89 x 36	59 x 62	84 x 29
54 x 73	84 x 53	56 x 31	87 x 52	56 x 89	89 x 56	59 x 63	84 x 39

Note. RD problems: Problems for which the rounding-down strategy was the better strategy and required; RU problems: Problems for which the rounding-up strategy was the better strategy and required.

Pictures. Ninety-six pictures were selected from the *International Affective Pictures System* (IAPS; Lang, Bradley, & Cuthbert, 2008; see Table 3 for the list of pictures). Half the pictures were emotionally negative (*mean* valence = 1.84; *SD* = .30, and *mean* arousal = 6.75; *SD* = .27), and half were emotionally neutral (*mean* valence = 5.26; *SD* = .32, and *mean* arousal = 2.99; *SD* = .35)[1]. Each picture was presented twice, once with a RD problem and once with a RU problem. Therefore, arousal and valence of neutral and negative pictures were matched across the RD and the RU problems.

Table 3. IAPS references of pictures used in the present study (Lang et al., 2008)

Neutral Pictures	Negative Pictures
2002, 2020, 2036, 2038, 2102, 2190, 2235,	2730, 2811, 3000, 3001, 3010, 3030, 3053,
2357, 2881, 2384, 2393, 2480, 2513, 2518,	3059, 3060, 3063, 3064, 3068, 3069, 3071,
2570, 2580, 2593, 2850, 2870, 2880, 2980,	3080,3100, 3102, 3110, 3120, 3130, 3131,
5533, 5534, 5740, 6150, 7000, 7001, 7002,	3140, 3150, 3170, 3195, 3266, 3400, 3500,
7004, 7009, 7035, 7036, 7039, 7041, 7052,	3530, 6312, 6313, 6350, 6520, 6563, 9050,
7057, 7062, 7080, 7161, 7179, 7185, 7187,	9163, 9183, 9187, 9252, 9410, 9414, 9635.1,
7233, 7300, 7490, 7493, 7500, 8312	9810, 9908, 9921, 9940

Procedure

The procedure is illustrated in Figure 1. The experiment was programmed with E-Prime software (Psychology Software Tools Inc., Pittsburgh, PA). Participants were told that they will see emotionally neutral or unpleasant pictures and will complete an arithmetic computational estimation task. Each trial started with a 500-ms fixation cross. Then, a picture which could be emotionally neutral (e.g., *mushrooms*) or emotionally negative (e.g., *a corpse*) was displayed on the screen for 2000 ms. Following this picture, the multiplication problem appeared superimposed on the picture until participants' response. Participants had to estimate, as quickly

[1] To check that valence and arousal differed for neutral and negative pictures for participants who participated in this experiment, participants were asked to rate each picture in terms of valence and arousal. Following the normative rating procedure for IAPS pictures (Lang et al., 2008), participants provided their ratings on a 9-point scale (1 being most negative on the valence scale and least exciting on the arousal scale). Neutral pictures (*mean* valence = 5.46; *SD* = .41; *mean* arousal = 2.30; *SD* = 1.24), and negative pictures (*mean* valence = 1.91; *SD* = .67; *mean* arousal = 7.01; *SD* = 1.52) significantly differed both for valence, $F(1,94) = 985.131$, $p < .001$, $MSe = .306$, $\eta^2p = .91$, and for arousal, $F(1,94) = 274.500$, $p < .001$, $MSe = 1.937$, $\eta^2p = .75$.

and accurately as possible, the product of the multiplication problem by executing the required computational estimation strategy among two strategies. The rounding-down strategy consisted in rounding both operands down to their nearest decades (e.g., multiplying 60 x 50 to estimate 64 x 52) and the rounding-up strategy consisted in rounding both operands up to their nearest decades (e.g., multiplying 60 x 30 to estimate 59 x 26). Following participants' response, a blank screen appeared for 500 ms. To reduce MEG signal contamination by speech articulation, and following previous studies (e.g., Ardiale & Lemaire, 2012; Lemaire et al., 2004; Lemaire & Hinault, 2014; Uittenhove & Lemaire, 2013b), participants were asked to vocalize only their final answer, after which a 500-ms blank screen appeared followed by the next problem which was displayed following a mouse-click by the experimenter. All participants completed a block of 96 trials with the rounding-down strategy on problems for which the rounding-down strategy was the most relevant, and another block of 96 trials with the rounding-up strategy on problems for which the rounding-up strategy was the most relevant. Half the participants started with the rounding-down strategy and the other half with the rounding-up strategy. Participants started each block of trials with a practice phase consisting of 10 trials (five neutral, five emotional), to become familiar with each computational estimation strategy.

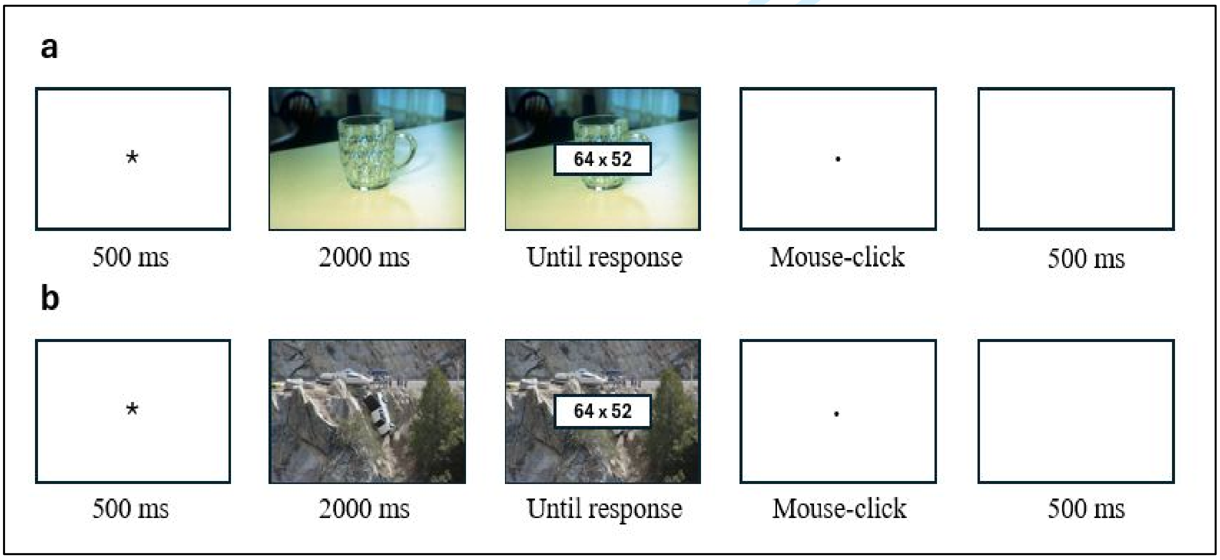

Figure 1. Sequence of events within examples of (a) an emotionally neutral trial, and (b) an emotionally negative trial.

MEG recording

The data were acquired at La Timone Hospital in Marseille, using a 248-channel whole-head 4D Neuroimaging MEG system, at a sampling rate of 2034.35 Hz. The electrooculogram and the electrocardiogram were recorded to assess eye movements and heartbeats, respectively. Five head-positioning coils were attached to the forehead and to the periauricular points to determine the position of the head. The individual head shape, consisting of the forehead, nose, and the location of the head-position coils, was digitized (Polhemus Fastrak; Polhemus Inc., Colchester, VT). Participants were lying on a hospital bed inside a magnetically shielded room. Stimuli were presented on an 800 × 600 resolution screen placed about 45 cm above participants, using a 48-point bold Courier font (black color), using a standard video projector. The visual angle was 1.4°. Head position inside the MEG helmet was measured at the beginning and the end of every block. Head displacements were monitored for remaining under 5 mm within each block, during the run and between the runs. The exact timing of visual presentation was captured using a trigger square projected onto a photodiode, invisible to the participant, that detected brightness changes on the presentation screen. This device also enabled synchronization between EOG/ECG and MEG recordings.

MEG Analyses

Artifact and channel rejection (on continuous data), and filtering (0.5-120 Hz bandpass, on unepoched data) were performed using Anywave (Colombet et al., 2015) and Brainstorm (Tadel et al., 2011). Continuous data were visually inspected to identify physiological (e.g., blinks, saccades, heartbeats) and non-physiological (e.g., bad sensors) artifacts. Time segmentation into 1.5 or 2-sec epochs, averages, and source estimation were all performed using Brainstorm. Epoching of trials was time-locked to the onset of the multiplication problem on the picture, and included 500 ms of pre-picture baseline (i.e., fixation cross display). We selected this period as baseline, as it was not influenced by emotional pictures or arithmetic processing. Artifact-free epochs for each experimental condition (i.e., RD/RU problems x Neutral/Negative conditions) were extracted from (a) -2000 to 0 ms, (b) 0 to 1500 ms, and (c) 1500 to 3000 ms around the onset of the multiplication problem and were averaged separately to obtain event-related magnetic fields (ERFs) in each participant. A free orientation minimum norm estimation (MNE) procedure was applied to estimate the cortical origin of the brain responses (Hämäläinen & Ilmoniemi, 1994; Hauk, 2004). The MNE was weighted by a sample estimate of sensor noise covariance matrix (Dale et al., 2000) obtained from the pre-picture period used as baseline (i.e., fixation cross period). The MEG forward model was obtained from overlapping spheres fitted to each participant's scalp points (Huang, Mosher, & Leahy, 1999). Brainstorm was used with default parameters to deform the template to each participant's digitized head shape (see Leahy et al., 1998, for technical details). The norm of the three source time series at each cortical voxel (i.e., conversion of orientation-unconstrained sources to flap maps, taking the norm of the three elementary dipoles at each time stem, yielding only one value by vertex) was extracted and *z*-scored with respect to the pre-picture baseline.

For several brain regions defined using the Desikan-Killiany cortical atlas (Desikan et al., 2006), differences in source activations between the emotionally negative and the emotionally neutral conditions in the 0 to 1500 ms after the onset of the multiplication problem time window were tested for significance using permutations of trials across conditions, with cluster-based correction to correct for multiple comparisons (Maris & Oostenveld, 2007). The purpose of contrasting these two emotional conditions in this specific time window was to determine effects of negative emotions on the neural bases of arithmetic processes that participants executed to solve the arithmetic problems. We also performed the same comparisons between negative and neutral conditions in (a) -2000 to 0 ms before the onset of the problems (i.e., corresponding to the onset of the pictures) and (b) 1500 to 3000 ms after the onset of the problems time windows to determine the neural bases of emotional pictures processing and effects of negative emotions on the neural bases of very late arithmetic processes.

Results

Results are reported in two parts. First, we investigated effects of negative emotions on participants' arithmetic performance. Then, we examined the spatial-temporal dynamics of brain activations during the execution of computational estimation strategies under emotionally negative and neutral conditions.

Behavioral results

Effects of negative emotions on arithmetic performance were analyzed via mixed-design ANOVAs on mean response times for correct responses and percentages of correct responses, involving 2 (Strategy: Rounding-up, Rounding-down) x 2 (Emotion: Negative, Neutral) within-participants designs (see Table 4 for *means* and Table 5 for summary of statistical results).

Table 4. Participants' *mean* response times (in ms) and percentages of correct responses (*SDs* in parentheses) as a function of Strategy (Rounding-up, Rounding-down) and Emotion (Negative, Neutral).

Strategy	Negative	Neutral	*Means*	*Effects of Emotion*
		Response Times (ms)		
Rounding-Up	4750 (1430)	4544 (1307)	4647 (1366)	**205** ***
Rounding-Down	3196 (947)	3086 (950)	3141 (945)	**110** **
Means	*3973 (1437)*	*3815 (1352)*	*3894 (1394)*	***158 ****
Effects of Strategy	1554 ***	1458 ***	1506 ***	-
		Percentages of Correct Responses		
Rounding-Up	87.4 (10.0)	87.5 (9.4)	87.5 (9.7)	**-0.1**
Rounding-Down	92.3 (5.8)	92.7 (6.0)	92.5 (5.9)	**-0.5**
Means	*89.9 (8.5)*	*90.1 (8.2)*	*90.0 (8.4)*	***-0.2***
Effects of Strategy	-4.8 ***	-5.3 ***	-5.0***	-

Note. Effects of Strategy: Rounding-up – Rounding-Down; Effects of Emotion: Negative – Neutral.

Table 5. Statistics of effects for response times (ms) and percentages of correct responses. ANOVAs: 2 (Strategy: Rounding-up, Rounding-down) x 2 (Emotion: Negative, Neutral).

Effects	*MSe*	*Fs*	η^2p
	Response Times (ms)		
Strategy	697,759	156.04	.77 ***
Emotion	56,513	21.08	.31 ***
Strategy x Emotion	58,330	1.88	.04
	Percentages of Correct Responses		
Strategy	71.876	17.01	.27 ***
Emotion	14.595	.19	.004
Strategy x Emotion	9.113	.24	.005

Response times. Latencies larger than the *mean* of the participant's *mean* + 2.5 *SDs* were removed (2.7%). Participants were slower with the rounding-up strategy than with the rounding-down strategy (4647 ms *vs*. 3141 ms), $F(1, 47) = 156.04$, $p < .001$, $MSe = 697{,}759$, $\eta^2p = .77$. Moreover, participants were slower in the negative condition than in the neutral condition (3973 ms *vs*. 3815 ms), $F(1, 47) = 21.08$, $p < .001$, $MSe = 56{,}513$, $\eta^2p = .31$. Finally, although the effects of negative emotions (i.e., differences in response times between negative and neutral conditions) were descriptively larger with the rounding-up strategy than with the rounding-down strategy (205 ms *vs*. 110 ms), the Strategy x Emotion interaction was not significant, $F(1, 47) = 1.88$, $p = .18$, $MSe = 58{,}330$, $\eta^2p = .04$.

An in-depth examination of individuals data revealed two profiles (see Figure 2 for a graphical representation). Indeed, out of the total sample of 48 participants, 36 participants were slower in the emotionally negative condition than in the emotionally neutral condition (4142 ms *vs*. 3889 ms), $F(1, 35) = 64.33$, $p < .001$, $MSe = 35{,}94$, $\eta^2p = .77$, while 12 participants were faster in the emotionally negative condition than in the emotionally neutral condition (3465 ms *vs.* 3595 ms), $F(1, 11) = 30.30$, $p < .001$, $MSe = 6{,}710$, $\eta^2p = .73$[2].

Interestingly, restricted analyses on the 36 participants who showed deleterious effects of negative emotions on response times revealed a significant Strategy x Emotion interaction, $F(1, 35) = 5.01$, $p = .032$, $MSe = 64{,}694$, $\eta^2p = .13$, showing larger effects of negative emotions with the rounding-up strategy (348 ms; $F(1,35) = 31.05$, $p < .001$, $\eta^2p = .47$) than with the rounding-down strategy (159 ms; $F(1,35) = 14.93$, $p < .001$, $\eta^2p = .30$).

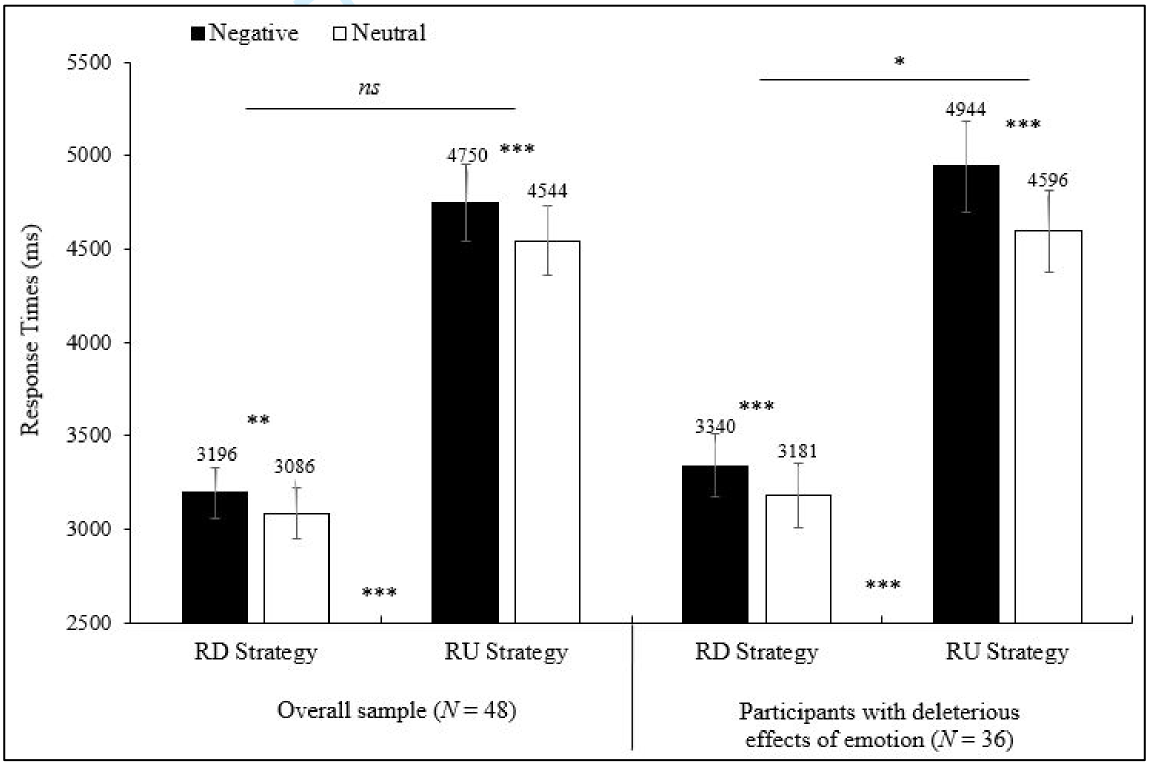

Figure 2. Response Times (ms) in overall sample ($N = 48$) and in participants with deleterious effects of negative emotion ($N = 36$) as a function of emotional condition (neutral, negative) and strategy (RD, RU). Errors bars represent S.E.M. *p<.05, **p<.01, ***p<.001, *ns*: non-significant, RD: rounding-down strategy, RU: rounding-up strategy.

[2] The group of participants who showed deleterious effects of emotions and the group of participants who showed beneficial effects of emotions were significantly different on effects of negative emotions (258 ms *vs.* -157 ms; $SE = 44.31$, $t(31.46) = 9.35$, $p < .001$), but not on other variables such as response times in the neutral condition (3838 ms *vs.* 3574 ms; $SE = 313.28$, $t(22.47) = .84$, $p = .41$), arithmetic fluency assessed with French Kit scores (35.8 *vs.* 36.1, $SE = 3.80$, $t(28.17) = -.08$, $p = .94$), vocabulary fluency assessed with MHVS scores (18.8 *vs.* 16.8, $SE = 1.28$, $t(18.319) = 1.600$, $p = .127$), general anxiety assessed with STAI scores (43.3 *vs.* 45.1, $SE = 3.14$, $t(20.72) = -.56$, $p = .58$), and mathematics anxiety assessed with sMARS scores (60.7 *vs.* 54.7, $SE = 4.72$, $t(28.61) = 1.28$, $p = .21$).

Accuracy. Participants were more accurate with the rounding-down strategy than with the rounding-up strategy (92.5% *vs*. 87.5%), $F(1,47) = 17.01$, $p < .001$, $MSe = 71.87$, $\eta^2 p = .27$. No other effects on either response times or percentages of correct responses came out significant.

MEG results

The MEG analyses compared activations in emotionally negative and neutral conditions in three time windows: (a) -2000 to 0 ms before the onset of the multiplication problem (i.e., corresponding to emotional picture processing), (b) 0 to 1500 ms after the onset of the multiplication problem, and (c) 1500 to 3000 ms after the onset of the multiplication problem.

-2000 – 0 ms time window. Cluster-based permutation tests restricted to participants who showed deleterious effects of negative emotions on behavioral performance ($N = 34$)[3] revealed significant differences in brain activations between the emotionally negative and neutral conditions during the -2000 to 0 ms before the onset of the arithmetic problem time window (i.e., corresponding to the display of the picture) in the left precentral and postcentral regions. Indeed, larger amplitude activations were found in the left precentral regions (i.e., localized in frontal lobe; $p = .022$) and in the left postcentral regions (i.e., primary somatosensory cortex localized in parietal lobe; $p = .020$) in the emotionally negative condition relative to the neutral

[3] Analyses were conducted on 34 participants instead of 36, due to the loss of MEG data from two participants.

condition, from -1600 to -1570 ms before the onset of the multiplication problems (see Figure 3).

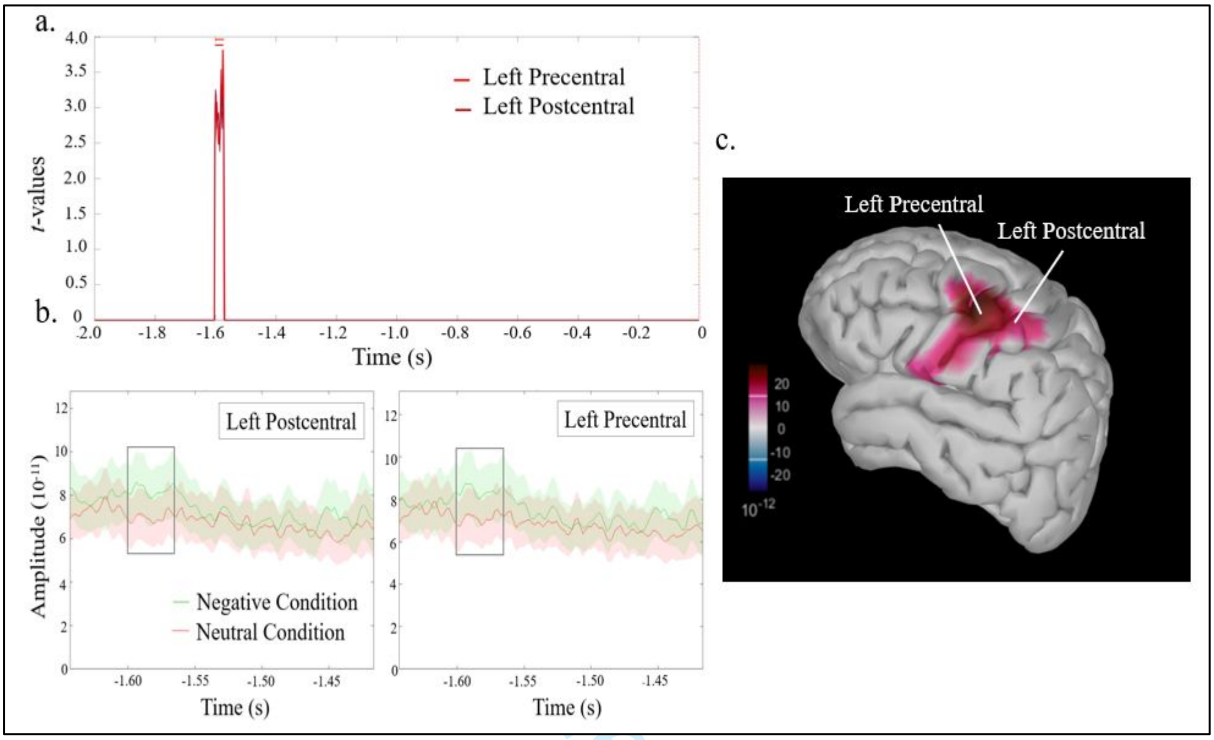

Figure 3. a. Results of cluster-based permutation tests (negative *vs.* neutral conditions) in left precentral and postcentral regions on participants who showed deleterious effects of negative emotions on behavioral performance ($N = 34$). Plotted are t-values from -2000 to 0 ms (time-locked to the onset of the multiplication problem). The light and dark red lines represent significantly larger activations in left precentral and left postcentral regions respectively in the negative condition compared with the neutral condition from -1600 to -1570 ms before the onset of the problem. **b.** Time course of activations of left precentral and left postcentral regions in negative (green) and neutral (red) conditions. The box represents the period for which larger activations in the negative condition compared with the neutral condition were significant (from -1600 to -1570 ms before the onset of the problem). **c.** Differences in amplitudes for left precentral and postcentral regions between negative and neutral conditions. Red colored areas represent larger activations in the negative condition compared with the neutral condition in left precentral and postcentral regions at -1580 ms before the onset of the problem.

0 – 1500 ms time window. Cluster-based permutation tests on the overall sample of participants (*N* = 46)[4] revealed significant differences in brain activations between the emotionally negative and neutral conditions during the 0 to 1500 ms after the onset of the arithmetic problem time window in the left superior parietal region. Indeed, smaller amplitudes were found in the left superior parietal regions for emotionally negative condition relative to emotionally neutral condition, from 140 to 220 ms after the onset of the multiplication problem on the picture (p = .002; see Figure 4).

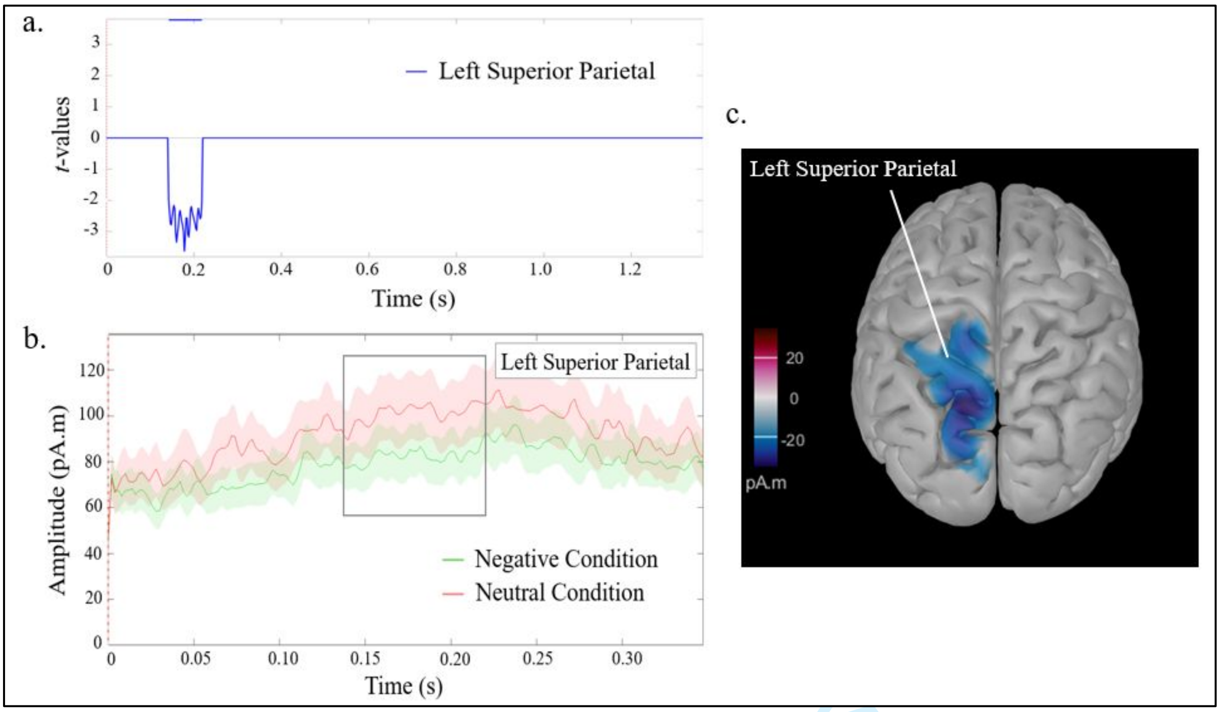

Figure 4. a. Results of cluster-based permutation tests (negative *vs.* neutral conditions) in left superior parietal regions on the overall sample of participants (*N* = 46). Plotted are *t*-values from 0 to 1300 ms (time-locked to the onset of the multiplication problem). The blue line represents significantly smaller activations in left superior parietal cluster in the negative condition compared with the neutral condition from 140 to 220 ms after the onset of the problem. **b.** Time course of activations of left superior parietal regions in negative (green) and neutral (red) conditions. The box represents the period for which smaller activations in the negative condition compared with the neutral condition were significant (from 140 to 220 ms after the onset of the problem). **c.** Differences in amplitudes for left superior parietal regions between negative and neutral conditions. Blue colored area represents smaller activations in the negative condition compared with the neutral condition in left superior parietal regions at 170 ms after the onset of the problem.

[4] Analyses were conducted on 46 participants instead of 48, due to the loss of MEG data from two participants.

Moreover, analyses restricted to participants who showed deleterious effects of negative emotions on behavioral performance revealed smaller amplitudes in the left precuneus in the emotionally negative condition relative to the neutral condition, from 240 to 275 ms after the onset of the multiplication problems (*p* = .030; see Figure 5).

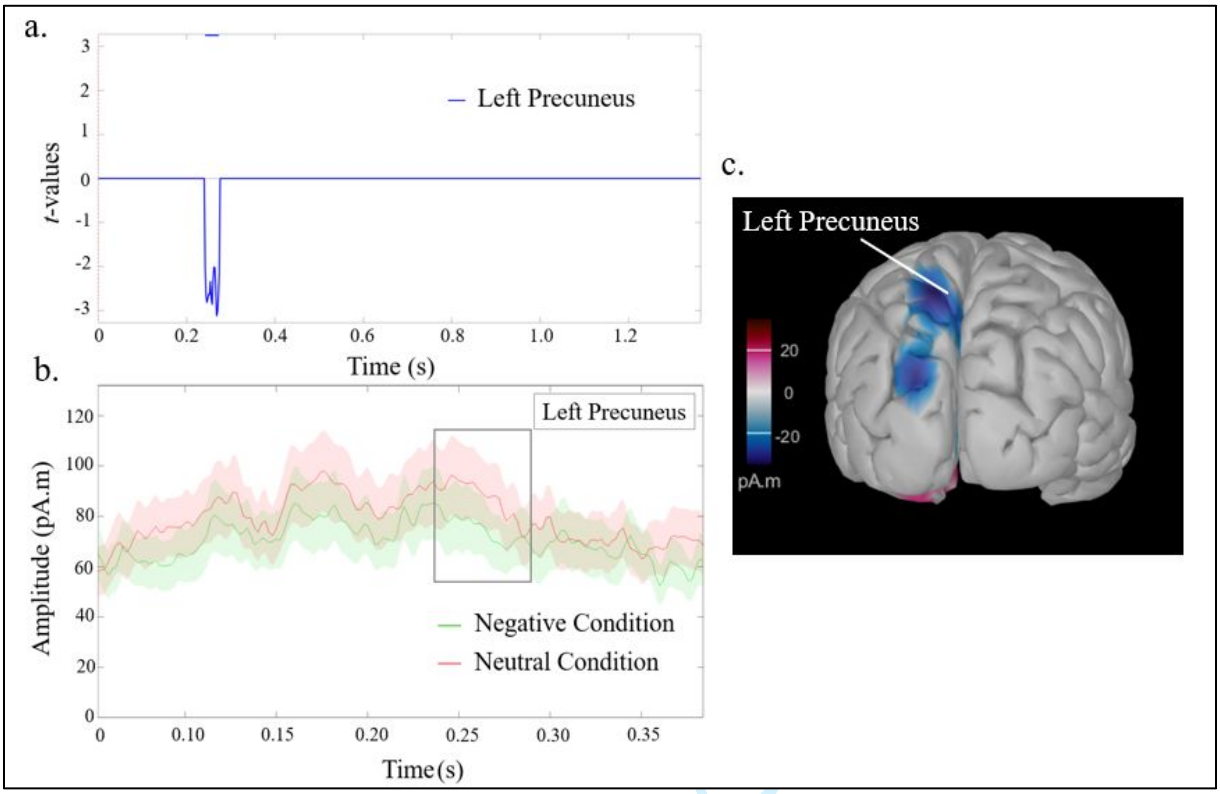

Figure 5. **a.** Results of cluster-based permutation tests (negative *vs.* neutral conditions) in left precuneus on participants who showed deleterious effects of negative emotions on behavioral performance (*N* = 34). Plotted are *t*-values from 0 to 1300 ms (time-locked to the onset of the multiplication problem). The blue line represents significantly smaller activations in left precuneus cluster in the negative condition compared with the neutral condition from 240 to 275 ms after the onset of the problem. **b.** Time course of activations of left precuneus in negative (green) and neutral (red) conditions. The box represents the period for which smaller activations in the negative condition compared with the neutral condition were significant (from 240 to 275 ms after the onset of the problem). **c.** Differences in amplitudes for left precuneus between negative and neutral conditions. Blue colored area represents smaller activations in the negative condition compared with the neutral condition in left precuneus at 260 ms after the onset of the problem.

1500 – 3000 ms time window. No differences in activations between the negative and the neutral conditions were found in the 1500-3000 ms time window.

General Discussion

The present study aimed at determining how negative emotions influence arithmetic performance. To address this issue, we used a within-trial emotion induction procedure while participants solved arithmetic problems. We adopted a strategy approach by manipulating the strategies used by participants to perform the arithmetic task and used the MEG technique to collect spatial and temporal brain activations in addition to behavioral performance. Participants had to estimate the products of two two-digit multiplication problems superimposed on emotionally negative or neutral pictures. They were required to execute a strategy among two computational estimation strategies on a first set of problems and another strategy on another, matched set of problems. We tested three sets of hypotheses regarding (a) how negative emotions influence arithmetic performance, (b) which mechanisms (i.e., domain-general, and/or domain-specific mechanisms) are influenced by emotions, and (c) which processing steps within computational estimation strategies are specifically or not specifically influenced by emotions. Our results replicated previously found deleterious effects of negative emotions on arithmetic performance, when strategic aspects of performance were controlled (e.g., Lemaire, 2024). Moreover, deleterious effects of negative emotions were larger while participants executed harder than on easier computational estimation strategies. MEG data revealed smaller activations under emotionally negative conditions of parietal brain regions known to be specifically involved in arithmetic processes, and no differences between the negative and the neutral conditions in activations of regions involved in domain-general functions (e.g., prefrontal regions). Moreover, differences in activations of parietal regions under negative emotions occurred very shortly after the onset of the arithmetic problems and were not found in later time windows. These findings have important implications for furthering our understanding of how negative emotions affect arithmetic performance.

Effects of negative emotions on arithmetic performance

We found poorer performance when participants solve arithmetic problems under negative than under neutral emotions, consistent with previous findings (e.g., Fabre & Lemaire, 2019; Fabre, Melani, & Lemaire, 2022; Framorando & Gendolla, 2018, 2019; Kleinsorge, 2007, 2009; Lallement & Lemaire, 2021, 2023; Liu et al., 2021; Melani, Fabre, & Lemaire, 2024; Schimmack, 2005; Zhu et al., 2021, 2022). These deleterious effects of negative emotions on arithmetic performance are usually assumed to result from negative emotions automatically capturing participants' attention, leading participants to be distracted away from the target arithmetic task and to perform more poorly. By instructing participants which strategy to execute on each arithmetic problem, the present study, controlled for (a) individual differences related to strategies used to perform the arithmetic task, (b) the possibility that participants use different strategies in the negative emotion condition compared to the neutral emotion condition. Thus, our results of decreased performance under negative emotions suggest that negative emotions impair execution of strategies used by participants to complete an arithmetic task. This is not incompatible with the attentional capture account commonly discussed in the literature regarding the effects of emotions on cognition (Okon-Singer et al., 2015; Pessoa, 2009; Verbruggen & De Houwer, 2007). Indeed, in our study, negative pictures may have captured the attention of participants, who either had to completely inhibit irrelevant emotional processing and/or had to divide their attentional resources between emotional and arithmetic processing. This may have led participants to execute computational estimation strategies less efficiently (more slowly).

Analyses restricted to the group of participants who showed deleterious effects of negative emotions revealed an interesting interaction between the type of strategy and the emotional condition. Deleterious effects of negative emotions were larger while participants executed the rounding-up strategy compared than with the rounding-down strategy. All previous studies comparing these two strategies found that rounding-up is harder than rounding-down (e.g., Lemaire & Lecacheur, 2010; Taillan et al., 2015; Uittenhove & Lemaire, 2012, 2013; Uittenhove et al., 2013). This is because, when they execute the rounding-up strategy, participants need to increment decade digits that are displayed on the computer screen, whereas they just need to encode and directly multiply the decade digits that are displayed with the rounding-down strategy. Moreover, computations with the RU strategy involve manipulating digits of larger size. As harder computational estimation strategies are more resource-demanding, with fewer available resources as a result of irrelevant emotional processing, participants' performance suffered more from negative emotions on harder than on easier strategies.

In sum, behavioral results have highlighted that negative emotions could exert their deleterious effects on performance by disrupting the execution of strategies participants use to perform the task, especially while executing a harder strategy. This result of larger deleterious effects of negative emotions on harder strategies highlights the importance of controlling or considering strategies used by participants to complete the task, since variations in effects of emotions could stem from the use of more resource-dependent strategies. Indeed, participants may obtain poorer performance under negative emotion conditions because they use different types of strategies, use harder strategies more often, select best strategy on each problem less often, and/or execute strategies more poorly. The present study controlled for all strategic aspects, but strategy execution. Still, we found deleterious effects of negative emotions. This does not mean that strategy execution is the only source of effects of deleterious effects of emotions. Previous works found that emotions also influence other strategic aspects (Lemaire, 2024). However, our study enabled to be sure that participants executed exactly the same strategies under negative and neutral emotion conditions. The next step is to determine whether negative emotions impair domain-general or domain-specific processes involved in arithmetic, and whether emotions impair execution of some specific procedures, or all procedures within strategies. The present MEG data provide important insights into these issues.

Neural bases of deleterious effects of negative emotions on arithmetic performance

MEG data enabled us to examine neural mechanisms by which negative emotions influence arithmetic performance, whether negative emotions influence domain-specific or domain-general mechanisms and which processing steps within computational estimation strategies are specifically impaired under negative emotion.

Brain results showed lower activations of **left superior parietal regions** (i.e., including **intraparietal sulcus** and **superior parietal lobule**) under negative emotions, compared to neutral emotion. Similar results were found when analyses were restricted to the group of participants who showed deleterious effects of emotions on behavioral performance, with lower activations of **left precuneus** under negative emotion, compared to neutral emotion. Activation of intraparietal sulcus when performing arithmetic tasks is one of the most robust results in previous studies on neural bases of arithmetic (see Cohen Kadosh, Lammertyn, & Izard, 2008; Dehaene et al., 2004; Menon, 2015, Nieder & Dehaene, 2009; Peters & De Smedt, 2018, for reviews). Particularly, the intraparietal sulcus is known to be involved in processing as well as manipulating magnitudes and numerical quantities in several numerical and arithmetic tasks (e.g., Burbaud et al., 1999; Chochon et al., 1999; De Visscher et al., 2015; Dehaene et al., 1999; Lee, 2000; Pesenti et al., 2000; Stanescu-Cosson et al., 2000). Also, among the many studies that have shown the involvement of parietal regions in arithmetic, some have highlighted the involvement of left superior parietal lobule and left precuneus in arithmetic functions (see Arsalidou et al., 2015; Arsalidou & Taylor, 2011; Dehaene et al., 2005; Hawes et al., 2019, for reviews). More precisely, studies have highlighted the involvement of left superior parietal lobule and left precuneus in number comparison (e.g., Pesenti et al., 2000; Pinel et al., 2001), approximation (e.g., Dehaene et al., 1999), counting (e.g., Sathian et al., 1999), verifying arithmetic problems (e.g., Liu et al., 2017; Price, Mazzocco, & Ansari, 2013; Rickard et al., 2000; Wu et al., 2009), and solving arithmetic problems of all four operations (e.g., Andres et al., 2011; Andres, Michaux, & Pesenti, 2012; Chang et al., 2019; Grabner et al., 2009; Kong et al., 2005; Lee et al., 1999; Peters et al., 2016; Rosenberg-Lee et al., 2009).

Decreased activations of left superior parietal regions (intraparietal sulcus and superior parietal lobule) and left precuneus under negative emotions could be the neural correlates of deleterious effects of negative emotions on execution of computational estimation strategies found in behavioral data. These results are consistent with Iordan and colleagues (2013)'s proposal that deleterious effects of irrelevant emotions on cognitive performance may result from decreased activations of brain regions crucial for target cognitive tasks. In our task, participants would share attentional resources between irrelevant emotional stimuli and arithmetic problems. Sharing of resources between emotional and arithmetic processing would result in reduced activations of brain regions involved in arithmetic processing in the negative emotion condition, compared to the neutral emotion condition. Under neutral condition, all or at least a larger proportion of cognitive resources could be allocated to the target arithmetic task.

Moreover, differences in activations between negative and neutral emotion conditions were only found in parietal regions. These regions are known to be specifically involved in arithmetic processes (see Arsalidou & Taylor, 2011; Menon, 2015; Peters & De Smedt, 2018, for reviews). The lack of differences in activations between the negative and neutral emotion conditions in regions known to be involved in domain-general functions such as working memory, cognitive control or attentional processes (e.g., prefrontal regions) suggests that emotions only impaired domain-specific processes while participants were accomplishing our computational estimation task, Interestingly, lower activations of left superior parietal regions and left precuneus occurred very shortly after the onset of the arithmetic problems (i.e., 140-220 ms for the left superior parietal regions and 240-275 ms for the left precuneus). Previous EEG studies in arithmetic have associated early components of evoked potentials to encoding processes (see Hinault & Lemaire, 2016; Muluh, 2011, for reviews). This suggests that, in our task, negative emotions disrupted early processing steps of problems solving, like encoding the operands, and did not disrupt later steps, such as calculation processes or response. Of course, this does not mean that calculation processes are insensitive to negative emotions. If emotions were triggering during the course of problem solving (e.g., displaying emotional picture slightly after showing problems) instead of before like here. Such a possibility may be tested in future studies.

Additional analyses of the time window preceding the onset of arithmetic problems (i.e., corresponding to the display of emotional pictures) revealed differences between negative and neutral conditions. Indeed, activations of **left precentral** (i.e., **precentral gyrus** localized in frontal lobe) and **left postcentral** (i.e., **postcentral gyrus/primary somatosensory cortex** localized in parietal lobe) regions were larger in the negative condition compared to the neutral condition, in participants who showed deleterious effects of negative emotions on behavioral performance. These results confirm that negative pictures were not processed in the same way as neutral pictures, as the processing of negative pictures engaged additional brain regions. Although precentral gyrus and postcentral gyrus are mainly known to be involved respectively in motor functions and somatosensory functions (see Penfield & Boldrey, 1937; Rizzolatti & Luppino, 2001, for reviews), several hypotheses can be proposed concerning their mobilization in the emotionally negative condition in the present study. First, a few studies have shown larger activations of **precentral gyrus** in conditions with emotionally negative stimuli as pictures or faces, compared to emotionally neutral conditions (e.g., Ferri et al., 2013; Frodl et al., 2009; Kesler et al., 2001; Morawetz et al., 2017; Pereira et al., 2010; Portugal et al., 2020). Several authors (e.g., Portugal et al., 2020; Ferri et al., 2013) proposed that activation of precentral gyrus during emotional processing, especially threatening stimuli, could activate motor areas to prepare participants to adapt their behavior and act if necessary. Alternatively, precentral gyrus is also known to be involved in flexible oculomotor control (e.g., Jin et al., 2022; Pierce & McDowell, 2016). In our task, it is possible that processing negative pictures required more flexible cognitive control, to try to disengage from the negative elements of pictures. As for **postcentral gyrus**, some studies have shown the involvement of somatosensory regions in emotional processing, such as perception, identification, or evaluation of emotional stimuli (e.g., Adolphs et al., 2000; Bolognini et al., 2013; Damasio et al., 2000; Kragel et al., 2016; Liddell et all., 2005; Orenius et al., 2017; Paracampo et al., 2017; Straube & Miltner, 2011; see Satpute et al., 2015, for a meta-analysis). Nevertheless, most of these studies reported the involvement of right secondary somatosensory regions, whereas we found activations in the left primary somatosensory cortex (i.e., left postcentral gyrus). Another hypothesis concerns empathy. Indeed, left postcentral gyrus is one of the regions known to be involved in the ability to share and understand the feelings of others and to be mobilized when participants see pictures, videos, or hear stories of people in pain (e.g., Ashar et al., 2017; Bufalari et al., 2007; Cheng et al., 2008; Gallo et al., 2018; Morrison et al., 2013; Nummenmaa et al., 2008; see Keysers, Kaas, & Gazzola, 2010; Lamm, Decety, & Singer, 2011 for reviews). Given that in the present study, most negative pictures depict people in pain (e.g., accidents, mutilations), it is highly possible that participants felt empathy.

Conclusions

The results of the present study provide further insight into the mechanisms by which negative emotions influence arithmetic performance. We have found that negative emotions disrupt the execution of computational estimation strategies, and even more so when participants use a harder strategy while solving arithmetic problems. Moreover, emotionally driven lower activations in regions involved in arithmetic at a very early step, together with lack of emotion-related changes in activations of brain regions not specifically involved in arithmetic (e.g., ventrolateral and dorsolateral prefrontal regions) suggest that emotions disrupt the first procedures within computational estimation strategies (such as problem encoding). This maybe the result of competing resources between irrelevant emotional processing and target arithmetic processing. Future studies should aim to determine whether the present findings of an early decrease in activations of regions involved in arithmetic under negative emotion generalize to (a) other arithmetic tasks, (b) other protocols in which participants are free to choose the strategies used to complete the task, and (c) other populations such as individuals with high and/or low levels of math anxiety. Additionally, since we previously found age-related differences in effects of negative emotions on arithmetic performance (Lallement & Lemaire, 2021), with older adults being less influenced by emotions than young adults, it would be interesting to conduct the present study in an older population and to determine the neural correlates of such differences so as to determine whether different mechanisms are influenced by emotions in different groups.

Data availability

Behavioral data can be found on the following link: https://osf.io/y6ust/?view_only=5505d0be513f43bf947deb87a2c59eb8

Authors contribution

C.L. and P.L. conceived the experiment. C.L. performed the data collection, analyses, and together with PL wrote several drafts of the manuscript. T.H. contributed to the data analyses and reviewed the manuscript. K.K. helped in the data collection and reviewed the manuscript.

Acknowledgments

We would like to thank Jean-Michel Badier for his technical help during the study implementation.

Funding

This research was supported by a grant from Agence Nationale de la Recherche to P.L. (Grant # ANR # 20-ASTC-0031) and a doctoral fellowship to C.L.

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