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Response monitoring in math-anxious individuals in an arithmetic task

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ABSTRACT

We examine whether math anxiety is related to altered response monitoring in an arithmetic task. Response-locked event-related brain potentials (ERPs) were evaluated in 23 highly (HMA) and 23 low math-anxious (LMA) individuals while they performed an arithmetic verification task. We focused on two widely studied ERPs elicited during error processing: error-related negativity (ERN) and error positivity (Pe). Correct-related negativity (CRN), an ERP elicited after a correct response, was also studied. The expected ERN following errors was found, but groups did not differ in its amplitude. Importantly, LMA individuals showed less negative CRN and more positive Pe amplitudes than their more anxious peers, suggesting more certainty regarding response accuracy and better adaptive behavioral adjustment after committing errors in an arithmetic task in the LMA group. The worse control over response performance and less awareness of correct responses in the HMA group might reduce their ability to 'learn from errors'.

1. Introduction

Many people see their opportunities at a professional level limited because they suffer from math anxiety, that is, they have feelings of tension when they face activities that involve handling numbers (for reviews see, for example, Ramirez et al., 2018; Suárez-Pellicioni et al., 2016). This anxiety leads them to perform poorly in mathematics and to avoid STEM (Science, Technology, Engineering and Mathematics) disciplines. Importantly, its prevalence among 15-year-olds in the Organisation for Economic Co-operation and Development (OECD) countries is very high: according to the Programme for International Student Assessment (PISA), 59% of these teenagers report often worrying about the difficulty of math classes and 30% feel nervous when solving math problems (Organization for Economic Co-operation and Development, 2013). Given the high prevalence of mathematics anxiety in the population and its relationship with poor performance in mathematics and avoidance of STEM disciplines, it is essential to investigate this issue in depth and seek solutions.

In recent years, the poor performance of highly math-anxious individuals in mathematics has been attributed to deficits in basic executive functions. According to the Attenional Control Theory (ACT; Eysenck et al., 2007), anxiety affects a key element of the central executive, attentional control, and, specifically, the most impaired functions in threatening situations would be inhibition and shifting. Thus, anxious people invest their attentional resources in anxiogenic stimuli, either internal (e.g., thoughts or worries) or external (e.g., irrelevant distractors for the task), compromising the execution of tasks that require attention. In the case of math anxiety, deficits in interference control (e.g., Suárez-Pellicioni et al., 2014, 2015) and in shifting function (González-Gómez et al., 2023) have been reported.

In addition to the basic executive functions proposed by Miyake et al. (2000), other authors (e.g., Mohamed et al., 2019) highlight another executive control process, error monitoring, which is necessary for error detection and adjustment of the response after making a mistake. According to Mohamed et al. (2019, p. 2218), "error monitoring [or what we term response monitoring] is a critical function for flexible interaction with changing environmental conditions…, and thus essential for learning and self-regulation". The study of this executive control process might be especially relevant in math-anxious individuals given the sensitivity they may have to the negative consequences of their failures in numerical tasks (Ashcraft & Kirk, 2001) and the role that response control plays in learning from mistakes. In this study, we aim to investigate whether math anxiety is related to inefficient response monitoring in arithmetic tasks.

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Response monitoring has traditionally been studied using event-related brain potentials (ERPs) and behavioral measures, as well as other psychophysiological indicators (e.g., heart rate, skin conductance, pupil dilation, etc.; for a review see Weinberg et al., 2012b). In this study, we will focus on ERPs and behavioral measures. Gehring et al. (1993) and Falkenstein et al. (1991) were the first to report a neural response to the commission of errors, which they referred to as error-related negativity (ERN) and the negativity associated with errors (Ne), respectively. ERN is a fronto-central negative component elicited approximately 0–100 ms after an erroneous response. Source localization studies have suggested that it is generated by a network of frontal brain regions, which includes the anterior cingulate cortex (ACC; a region involved in monitoring behavior that signals the need for increased cognitive control; Carter et al., 1998; Dehaene et al., 1994), as well as the prefrontal cortex (PFC; Edwards et al., 2012) and supplementary motor areas such as the pre-supplementary motor area (pre-SMA: Iannaccone et al., 2015).

Although the link between ERN and performance failures is a robust phenomenon, the specific functional significance of ERN remains under debate (Meyer & Hajcak, 2019). On the one hand, several studies have found ERNs of greater amplitude in people with anxiety, worrying and obsessive-compulsive disorders (OCD) (e.g., Moser et al., 2013; Olvet & Hajcak, 2008), when the error involves a monetary loss (Hajcak et al., 2005), or when precision is emphasized more than speed (Gehring et al., 1993). This is why this increase in ERN has been suggested to reflect a greater affective sensitivity or concern over making errors (Weinberg et al., 2016). However, an association between ERN and anxiety/OCD has not always been found (Gloe & Louis, 2021); some researchers suggest that this association depends on factors such as sex/gender differences (Moser et al., 2016), task instructions emphasizing accuracy or speed (Riesel et al., 2019a, 2019b), the inclusion of trial-to-trial accuracy feedback (Olvet & Hajcak, 2009c) or even the format in which the stimuli are presented (Lin et al., 2015). On the other hand, individuals who commit fewer errors show a larger ERN (e.g., Holroyd & Coles, 2002; but see Falkenstein et al., 2000, and Masaki et al., 2007, who found no relationship between error-rate and ERN) and the magnitude of ERN is positively correlated with better academic performance (Hirsh & Inzlicht, 2010), so it has been suggested that this component might reflect an increase in cognitive control or the compensatory effort made to avoid making mistakes.

After ERN, error positivity (Pe) is elicited. It is a more broadly distributed component across central and centroparietal electrode sites with a maximum positive peak that occurs between 200 and 400 ms after making a mistake (Ridderinkhof et al., 2009). The ACC has also been suggested as the primary generator of Pe (e.g., vanVeen & Carter, 2002). Pe has been related to conscious error awareness (Endrass et al., 2005; Klein et al., 2013; Shalgi et al., 2009) and to the allocation of attentional resources to error in order to improve subsequent performance (Ridderinkhof et al., 2009), although its sensitivity to individual differences in anxiety is controversial (Hajkak et al., 2004). Some authors find greater amplitudes in Pe related to anxiety (Weinberg et al., 2010), others a reduced Pe (Moser et al., 2012), and some find no relationship between the amplitude of the component and anxiety (Weinberg et al., 2012b).

Correct-response negativity (CRN) or correct negativity (Nc) is another event-related potential associated with response monitoring (Coles et al., 2001; Falkenstein et al., 2000). It is a fronto-central negative component, topographically and morphologically similar to ERN, but of smaller amplitude, that is observed after correct response execution. Bartholow et al. (2005) found that incompatible trials yield a larger CRN amplitude than compatible trials, suggesting that CRN is sensitive to response conflict and task-related conflict. Pailing and Segalowitz (2004) assumed that correct responses misjudged as errors elicit CRN, so it results from partial error processing on correct trials or decision uncertainty. Larger CRN amplitudes have also been reported in obsessive-compulsive patients compared with healthy control participants (Endrass et al., 2008), which suggests that this component is sensitive to cognitive impairments and alterations in the performance monitoring system.

To study response monitoring, it is also common to use another related measure: delta ERN (i.e., ΔERN or dERN), which is calculated by subtracting the CRN amplitude from the ERN amplitude. By eliminating shared neural activity found in both error and correct responses, ΔERN has been suggested to reflect activity unique to error-processing (Riesel et al., 2013). In addition, current recommendations advise isolating components of interest by creating difference waves (Luck, 2014). However, the magnitude of the difference in ΔERN can be due to changes in only ERN or CRN (Meyer et al., 2017), so here we will also study ERN and CRN separately.

As for the behavioral measures used to study response monitoring, two have been identified: *post-error slowing* (PES; Rabbitt, 1966) and *post-error accuracy* (PEA; Laming, 1979). PES is the slowdown in response times (RT) after making an error compared to the RT after correct responses. It has been proposed that this measure reflects a more cautious response strategy to improve performance in the subsequent trial (conflict monitoring account; Botvinick et al., 2001), the orienting response to infrequent events such as errors in simple tasks (orienting account; Notebaert et al., 2009) or a response inhibitory mechanism or motor suppression in the subsequent trial (inhibitory account: Ridderinkhof, 2002). On the other hand, PEA refers to the precision in the post-error trial and, unlike the PES, it is not always higher after an error has been made (Danielmeier & Ullsperger, 2011). The conflict monitoring account predicts a higher PEA, while the other two proposals predict a decrease in PEA.

Response monitoring investigations in math-anxious populations are scarce. To our knowledge, only one study by Suárez-Pellicioni et al. (2013) has reported differences in ERN amplitude related to math anxiety. Specifically, they found a larger ERN amplitude in highly math-anxious individuals compared to those with low anxiety when they made mistakes in a numerical Stroop task. There were no group differences either in post-error behavioral measures in this numerical task or in the ERN amplitude when errors in a classical Stroop task were analyzed. These results were interpreted in accordance with the ERN theory of motivational significance (Hajcak et al., 2005; Hajcak & Foti, 2008), suggesting that math-anxious people might be more sensitive or more concerned about their errors in tasks where they have to process numbers. Núñez-Peña et al. (2017) studied the behavioral response to mistakes of highly math-anxious individuals in an arithmetic verification task and no group differences were found either in PES or PEA. They only found that highly math-anxious individuals showed lower PEA if they had to repeat the motor response that had led them to make the previous mistake. Finally, another study worth mentioning is the one by Schillinger et al. (2016), who investigated the association between electrophysiological indices of response monitoring in a numerical Stroop task and test anxiety (a construct related to math anxiety; Hembree, 1990). They found the ΔERN increased linearly with individuals' test anxiety scores, although no relationship was found between ERN and test anxiety.

The aim of the current study was to further examine whether performance monitoring is altered in highly math-anxious individuals while they perform an arithmetic verification task, a complex cognitive task that requires attentional control (Raghubar et al., 2010) and has better ecological validity in a math context compared to the numerical Stroop task used by Suárez-Pellicioni et al. (2013). We studied differences between a highly and a low math-anxious group and focused on the ERPs discussed above to evaluate response-locked information processing (ERN, CRN, ΔERN and Pe) as well as indices of behavioral adjustment following errors (PES and PEA). Note that these brain potentials have generally been studied in simple choice reaction-time tasks (i.e., attentional control tasks such as flanker, Simon and Stroop tasks), but they have not yet been studied in an arithmetic task. If observed, this would extend the existing literature on response monitoring with ERPs to a more complex task.

Our predictions were as follows. Firstly, in terms of behavioral measurements, we expected highly math-anxious individuals to be slower and more error prone in the arithmetic task than their low math-anxious peers. We also expected to reproduce previous results on post-error behavior; i.e., an increase in response time (PES) after errors as compared to correct answers (i.e., Botvinick et al., 2001), and no group differences in this correlate (Suárez-Pellicioni et al., 2013). Secondly, in terms of ERPs, we predicted that highly math-anxious individuals would show impaired activation of response monitoring, which would lead them to show smaller differences between CRN and ERN (i.e., worse differentiation of their correct and incorrect responses) than their low math-anxious peers. Concerning ERN, it has been suggested that this component reflects greater affective sensitivity or concern over making errors (Weinberg et al., 2016), so highly math-anxious individuals may show enhanced ERN. We also expected the CRN amplitudes to be altered in highly math-anxious individuals, because they were expected to be not only particularly concerned about their errors, but also, they might have more doubts about the correctness of their actions in the math task. Given that CRN is sensitive to response conflict and is related to reduced certainty about the correctness of the actual response (Pailing & Segalowitz, 2004; Scheffers & Coles, 2000), we predicted that CRN amplitudes would also be enhanced in the more anxious group (Hajcak & Simons, 2002). Our last prediction for ERP measures is to do with Pe. If Pe reflects awareness of and allocation of attention to mistakes (Klein et al., 2007; Ridderinkhof et al., 2009), the highly math-anxious group may show reduced Pe amplitude.

2. Methods

2.1. Participants

Participants were 23 low math-anxious (LMA) and 23 highly math-anxious (HMA) undergraduate volunteers whose math and trait anxieties had previously been assessed within the framework of a larger project. A total sample size of at least 20 subjects in each group is required for a statistical power of 0.80, a Cohen's f effect size of 0.40 and an alpha level of 0.05 (Faul et al., 2007). Groups were formed based on participants' scores on the *Shortened Mathematics Anxiety Rating Scale* (SMARS; Alexander & Martray, 1989). The LMA group scored below the first quartile[1] ($Q_1 = 53$) and the HMA group above the third quartile ($Q_3 = 78$). Participants were also paired according to their scores in the *State-Trait Anxiety Inventory* (STAI; Spielberger et al., 1983) to ensure that group differences were not due to trait anxiety ($t(44) = .22$, $p = .82$, $d = .07$). No participants rating above the third quartile ($Q_3 = 33$) in the STAI-Trait were selected in order to ensure that the results obtained during the task were not due to high levels of trait anxiety. Groups did not differ in age ($t(44) = .08$, $p = .93$, $d = .02$) or gender distribution ($X^2(1) = 1.53$, $p = .22$). Table 1 shows means and SEMs for both groups in these variables as well as number of men and women.

Table 1
Means and SEM (in brackets) for math anxiety, trait anxiety and age for the LMA and HMA groups. Number of women and men is also given (women/men).

	Math Anxiety	Trait Anxiety	Age	Gender
LMA	43.78 (1.55)	18.00 (1.59)	22.43 (0.76)	13 / 10
HMA	89.17 (2.12)	18.48 (1.43)	22.35 (0.78)	17 / 6

[1] Quartiles were calculated in a sample of 1547 students at the University of Barcelona (78% females and 22% males) with a mean age of 21.92 years (SD = 5.15) in the framework of a larger project.

2.2. Materials

2.2.1. Shortened mathematics anxiety rating scale (Alexander & Martray, 1989)

The Spanish version of the SMARS was used to select the participants (Núñez-Peña et al., 2013). Núñez-Peña et al. (2013) adapted the scale and reported good parameters of internal consistency ($\alpha = .94$) and 7-week test-retest reliability ($r = .72$). The SMARS is formed by 25 five-point Likert-scaled items that participants must rate from 1 (no anxiety) to 5 (high anxiety) when imagining themselves dealing with different situations that might cause them math anxiety (e.g., "Thinking about the math exam I will have next week"). The final score represents participants' general levels of math anxiety, which ranges from 25 (low math anxiety) to 125 (high math anxiety).

2.2.2. State-trait anxiety inventory (Spielberger et al., 1983)

The 9th Edition of the STAI-Trait subscale's Spanish adaptation (Buela-Casal et al., 2015) was used to select the participants. It is formed by 20 four-point Likert-scaled items that participants must rate from 0 (almost never) to 3 (almost always), referring to different emotions they feel in general (e.g., "I get tired quickly"). The final score, which ranges from 0 (low anxiety) to 60 (high anxiety), represents a stable tendency to perceive situations as threatening and to consequently increase the state anxiety. Guillén-Riquelme & Buela-Casal (2015) analyzed its psychometric properties, reporting a good internal consistency of the present subscale ($\alpha = .94$).

2.2.3. Arithmetic verification task

The test comprised a list of 144 single-digit additions, including all possible operations resulting from adding numbers ranging from 2 to 9. Additions with the same operand were used in both directions (e.g., "2 + 5″ and "5 + 2″). In order to increase the number of participants' mistakes and produce enough trials for the ERN and post-error behavioral measurements, additions were selected considering several aspects. Firstly, additions with 1 or 0 as operands, with 10 as their true solution, and tie problems (i.e., with both operands being the same number; e.g., 3 + 3) were not used, because they might be easier to resolve and not require as much effort (Avancini et al., 2015). Secondly, incorrect solutions for each addition were obtained by adding and subtracting one unit to and from their true solution (i.e., small-split solutions, which are solved less accurately than large-split solutions; Ashcraft & Battaglia, 1978; e.g., we used 8 + 3 = 12 instead of 8 + 3 = 21). Finally, in order to prevent participants from using the most efficient parity rule (i.e., the result of adding two even numbers is always an even number; otherwise the answer is incorrect; Campbell et al., 2004), for those additions with both operands being even numbers, two units were added or subtracted instead of one (e.g., "6 + 8 = 12″ instead of "6 + 8 = 13″). For the "2 + 4″ and "2 + 6″ additions in both directions, their form resulting from adding two units to the true solution was used twice since their form resulting from subtracting two units produces a non-plausible solution (e.g., "2 + 4 = 4″). Three different blocks, with 48 additions each, were designed by keeping fixed the fact that the same exact addition was not repeated within the same block (e.g., "8 + 5 = 13″ and "8 + 5 = 14″). Each block included 16 correctly solved additions and 32 incorrectly solved additions (half of them were formed by adding 1 to the correct solution and the other half were formed by subtracting 1 from the correct solution). The full list of 144 simple additions was presented twice to each participant (i.e., a total of 6 blocks with 48 additions within each of them), in order to ensure enough errors for both behavioral and electrophysiological analyses.

2.3. Procedure

Participants were tested individually. They signed the informed consent before preparing the electroencephalogram (EEG) recording. Then, the EEG sensor cap with the electrodes was attached and the instructions for the task were given to the participants. They were seated 150 cm away from the computer screen in a sound-attenuating and electrically shielded recording chamber. Participants were asked to indicate whether the result presented after each addition was correct or incorrect by clicking on one of the two buttons of the mouse. Response buttons were counterbalanced between participants. The experimental session started with a training block of 10 trials, which contained additions that were not included in the experimental blocks, to familiarize participants with the task.

Each trial started with a window-centered fixation point (an asterisk) shown for 200 ms. Next, after presenting a blank screen for 100 ms, the simple addition appeared for 500 ms. Then, another blank screen was presented for 100 ms. Finally, a true or false solution appeared and remained on the screen until a response was detected or for up to 1500 ms. Each trial ended with a variable pause that ranged from 500 to 800 ms, during which the participants were asked to take the opportunity to blink if needed (an example of a trial is provided in Fig. 1). At the end of each block, there was another pause that lasted until whenever the participants decided to continue with the following block. A reminder of how they must respond was displayed after the training period and when the first three blocks had been completed (i.e., half of the experiment). Both the additions and the solutions were horizontally and vertically centered, in bold 50-point size Courier New font, and colored in white on a 640 × 480 pixel resolution black screen.

3. Electrophysiological recording

The EEG signal was recorded with Scan 4.5 hardware and software (Copyright (C) 2009, Compumedics Neuroscan, Inc., Herndon, VA) from 32 tin electrodes mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH. ANT Advanced Neuro Technology) and positioned according to the extended 10/10 International System: eight electrodes were placed on the midline at the FPz (placed on every participant at 10% of the nasion-inion distance), Fz, FCz, Cz, CPz, Pz, POz and Oz locations, along with 12 lateral pairs of electrodes that were placed on standard sites at the prefrontal (FP1/FP2), frontal (F3/F4, F7/F8), frontocentral (FC3/FC4), frontotemporal (FT7/FT8), central (C3/C4), temporal (T7/T8), centroparietal (CP3/CP4), temporoparietal (TP7/TP8), parietal (P3/P4, P7/P8) and occipital (O1/O2) positions. Two electrodes were placed on the right and left mastoids to be used as a re-reference. Likewise, the electro-cap was placed with the FPz electrode at 10% of the nasion-inion distance. The horizontal and vertical electrooculogram movements were recorded with two independent electrodes placed at the outer canthus of the right eye and below the left eye, respectively. The common reference electrode was placed on the tip of the nose and the ground electrode was located between Fz and FPz. EEG channels were continuously digitized at a rate of 500 Hz by an amplifier, and electrode impedance was kept below 5 kΩ.

4. Data analysis

4.1. Behavioral data

Medians of response times (RT) for correctly solved trials and hit rate were analyzed with independent *t*-tests to study group differences. Moreover, behavioral post-error adjustments were studied with ANOVAs of response time and hit rate, taking Previous-Trial Accuracy (Post-Error vs. Post-Correct) as the within-subject factor and Group (LMA vs HMA) as the between-subjects factor. Simple effect tests were performed whenever the interaction was significant using Bonferroni correction in order to control for the increase in Type I error. Differences between groups in the magnitude of post-error response slowing (i.e., PES; difference in RT for correct trials following error trials compared to correct trials following matched-correct trials) and post-error accuracy (i.e., PEA; difference in hit rate for trials following error trials compared to trials following correct trials) were analyzed with independent *t*-tests. Cohen *d* and partial eta squared (μ_p^2) effect-size indexes are reported.

4.2. EEG data

Pre-processing and analysis of the electrophysiological data was performed using EEGLAB 2022.1, a toolbox of MATLAB 9.13 (R2022b) software (The MathWorks, Inc). Data were first filtered with a band-pass filter from 0.5 to 30 Hz, and then re-referenced to the mastoids' mean activity. An independent components analysis was run using the Binica algorithm provided by EEGLAB (Lopez-Calderon & Luck, 2014) for correcting eye movement-related activity and other stereotypical artifacts. Non-stereotypical artifacts were previously manually rejected.

Response-locked ERPs were averaged independently for error and correct trials using ERPLAB. A baseline correction was applied using the − 200 to − 100 ms pre-response interval. The continuous signal was divided into − 400 to 600 ms epochs relative to the response onset. Data from two participants were excluded from the electrophysiological analysis because they committed less than six errors in the task (Olvet & Hajcak, 2009a). This left a final sample of 22 participants in each group for these analyses. The mean number of epochs included in each average for each participant was 236 (SEM = 4.78) for correct and 35 (SEM = 3.10) for error responses. Grand average waveforms were filtered with a 20-Hz low-pass filter for visual presentation.

The electrical activity of each participant's brain was synchronized to the moment when the response button was pressed. To quantify response-locked ERPs (ERN and CRN), we calculated the average amplitude occurring in a 0- to 100-msec post-response time window at the FCz electrode site. Moreover, we also analyzed the difference between error and correct trials (i.e. ΔERN = error - correct) in the same time window, because this measure is thought to isolate neural response to errors from brain activity more broadly related to response-monitoring (Simons, 2010). We selected FCz based on previous studies that showed that the ERN is largest there (Gehring et al., 2011). Moreover, good split-half and test-retest reliabilities for ERN, CRN and ΔERN have been reported using measures at the FCz site (Olvet & Hajcak, 2009b; Weinberg & Hajcak, 2011). ANOVAs for the 0–100 ms window mean amplitudes were performed, taking Response (error and correct) as the within-subject factor and Group (LMA and HMA) as the between-subjects factor. Simple effect tests were performed whenever the interaction was significant. We also performed independent *t*-tests to study group differences in ΔERN. Cohen *d* and partial eta squared effect-size indexes are reported.

To study Pe (Ullsperger & von Cramon, 2006; van Been & Carter, 2002), we computed the average amplitude in correct and incorrect trials from 150 to 250 msec following response onset across five

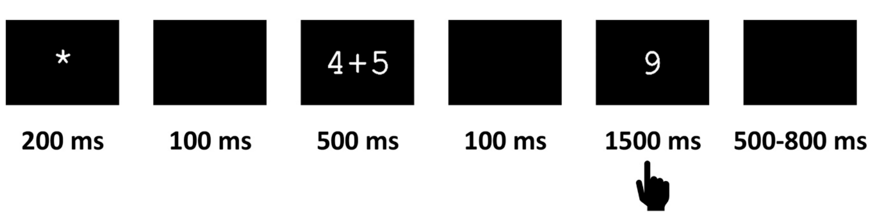

Fig. 1. An example of a trial is provided.

recording sites (Fz, FCz, Cz, CPz, Pz). We used these electrodes at the median line because, although several studies have found Pe to have a centro-parietal maximum (e.g., Grützmann et al., 2014), visual inspection revealed that Pe was largest at fronto-central sites. Again, a difference score subtracting the amplitude in error trials minus correct trials was calculated in the same time window (i.e., ΔPe). An ANOVA was performed taking Response (error and correct) and Frontality (Fz, FCz, Cz, CPz, Pz) as the within-subject factors and Group (LMA and HMA) as the between-subjects factor. Simple effect tests were performed whenever the interaction was significant. Cohen d and partial eta squared effect-size indexes are reported.

Correlation analyses (Spearman correlation coefficients) were conducted to examine the relationships between the measures of response-related brain activity (ERN, CRN, ΔERN, Pe and ΔPe), performance measures (RT, hit rate, PES and PEA), and self-reported measures (math anxiety and trait anxiety).

5. Results

5.1. Behavioral measures

HMA individuals were slower ($t(44) = 4.95$; $p < .001$; $d = 1.461$) and more error-prone ($t(44) = 5.37$; $p < .001$; $d = 1.584$) than their LMA peers. As for post-error adjustments on RT, the main effects for Previous-Trial Accuracy and for Group were significant ($F(1,44) = 26.33$, $p < .001$, $\mu_p^2 = .374$, and $F(1,44) = 18.18$, $p < .001$, $\mu_p^2 = .292$, respectively), but the interaction Previous-Trial Accuracy x Group did not reach significance ($F(1,44) = 1.06$, $p = .31$, $\mu_p^2 = .024$). Means showed that responses were slower after committing errors than after correct responses, but this PES did not differ between groups ($t(44) = 1.03$; $p = .31$; $d = 0.304$). Concerning post-error adjustments on hit rate, only the Group effect was significant ($F(1,44) = 12.17$, $p = .001$, $\mu_p^2 = .217$). The Previous-Trial Accuracy effect was marginally significant ($F(1,44) = 2.92$, $p = .095$, $\mu_p^2 = .062$): mean hit rates tended to be larger after correct responses than after committing mistakes. PEA did not differ between groups ($t(44) = 0.39$; $p = .69$; $d = 0.116$).

Table 2 shows means and SEMs for all the behavioral measures in both groups.

6. ERP measures

6.1. ERN and CRN

Fig. 2 depicts the response-locked grand average ERP waveforms at FCz for error and correct responses of LMA and HMA participants. Both groups showed a more pronounced ERN than CRN, which reached a maximum approximately 50 ms post-response. It also shows topographies of correct and incorrect responses in the 0–100 ms window for both groups.

The analyses performed on the mean amplitude in the 0–100-ms window revealed a significant main effect of Response ($F(1,42) = 54.28$, $p < .001$, $\mu_p^2 = .564$), showing a larger amplitude in error than in correct responses. These results are consistent with the presence of ERN. Importantly, this effect was modulated by the Response x Group interaction ($F(1,42) = 4.09$, $p = .05$, $\mu_p^2 = .089$). This interaction showed that although the mean amplitude was more negative after an error than after a correct response in both groups ($F(1,21) = 32.27$, $p < .001$, $\mu_p^2 = .606$ and $F(1,21) = 22.53$, $p < .001$, $\mu_p^2 = .518$, for the LMA and the HMA groups respectively), showing that ERN was present in both, this difference (ΔERN) was larger in the LMA than in the HMA group ($t(42) = 2.02$; $p = .05$; $d = 0.609$). A more detailed analysis of this difference showed that groups did not differ in their mean amplitude in error responses but did differ in correct responses (i.e. CRN was more negative in the HMA than in the LMA group; $t(42) = 2.65$; $p = .011$; $d = 0.799$). Fig. 3 shows difference waves (error minus correct response) for the LMA and HMA groups: it can be seen that ΔERN was larger in the former. It also shows the topography of ΔERN in both groups.

Table 2
Means and standard errors of the means (SEM; in brackets) for the LMA and HMA groups in all the behavioral measurements.

	RT	Hit rate	PES	PEA
LMA	531 (19.7)	.90 (.01)	122 (24.6)	.02 (.01)
HMA	718 (32.0)	.76 (.02)	81 (31.0)	.01 (.01)

Means and standard errors for ERN, CRN and ΔERN for the LMA and HMA group are shown in Table 3.

6.1.1. Pe

The ANOVA performed on the mean amplitude in the 150–250-ms window showed a significant main effect for Group ($F(1,42) = 5.16$, $p = .028$, $\mu_p^2 = .109$) and significant interactions for Response x Group ($F(1,42) = 4.24$, $p = .046$, $\mu_p^2 = .092$), Response x Frontality ($F(4168) = 9.89$, $p = .001$, $\varepsilon = .33$, $\mu_p^2 = .191$) and Response x Frontality x Group ($F(4168) = 2.70$, $p = .032$, $\varepsilon = .33$, $\mu_p^2 = .061$). In order to study these interactions in more detail, separate ANOVAs were performed for each frontality in the HMA and LMA groups. The results showed that the Response effect was only significant for the LMA group at the Fz ($F(1,21) = 8.38$, $p = .009$, $\mu_p^2 = .26$), FCz ($F(1,21) = 8.38$, $p = .009$, $\mu_p^2 = .285$), and Cz ($F(1,21) = 4.72$, $p = .041$, $\mu_p^2 = .184$) electrodes. For this group, errors elicited larger positivity than did correct responses (i.e., the presence of Pe). The Response effect was negligible for the HMA group. Analysis of ΔPe (amplitude difference between incorrect and correct responses) showed that amplitude was more positive for the LMA than for the HMA group at the Fz ($t(42) = 2.50$; $p = .047$; $d = 0.617$), FCz ($t(42) = 2.33$; $p = .024$; $d = 0.704$), and Cz ($t(42) = 2.14$; $p = .038$; $d = 0.645$) sites. Fig. 3 shows the topography of ΔPe in both groups. Means and standard errors for Pe and ΔPe for the LMA and the HMA group at FCz are shown in Table 3.

6.2. Correlation analysis

Correlation analysis showed that CRN amplitudes at FCz were negatively related to math anxiety scores ($r(44) = -.406$; $p = .006$) and response times in the arithmetic task ($r(44) = -.477$; $p = .001$), and positively related to accuracies (% of hits; $r(44) = .417$; $p = .005$). Positive associations were found between ΔERN and math anxiety scores ($r(44) = .392$; $p = .009$) and response times ($r(44) = .414$; $p = .005$). As for the ERN amplitudes, correlations with these measures were negligible.

Concerning Pe, the results showed significant negative correlations between Pe amplitudes at Cz and math anxiety scores ($r(44) = -.415$; $p = .005$) and response times ($r(44) = -.344$; $p = .022$), and a positive correlation with accuracies ($r(44) = .376$; $p = .012$). The same pattern of associations was found for ΔPe: $r(44) = -.305$, $p = .044$; $r(44) = -.293$, $p = .050$; and $r(44) = .392$, $p = .009$, for math anxiety scores, response times and accuracies, respectively. Finally, post-error behavioral measures (i.e., PES and PEA) were not associated with any of the ERP measures.

Table 4 shows Pearson correlation coefficients between ERP measures (ERN, CRN, ΔERN, Pe, and ΔPe), performance and self-reported measures. It can be seen that the brain activity in the windows that we analyzed was not related to trait anxiety.

7. Discussion

The goal of this study was to examine whether highly math-anxious individuals exhibit response monitoring deficits when they perform an arithmetic task compared to their low math-anxious peers. To this end, we studied group differences in post-error behavioral adjustment measures (i.e., PES and PEA), as well as in ERP amplitudes, focusing on the ERN, CRN and Pe components. To the best of our knowledge this is the

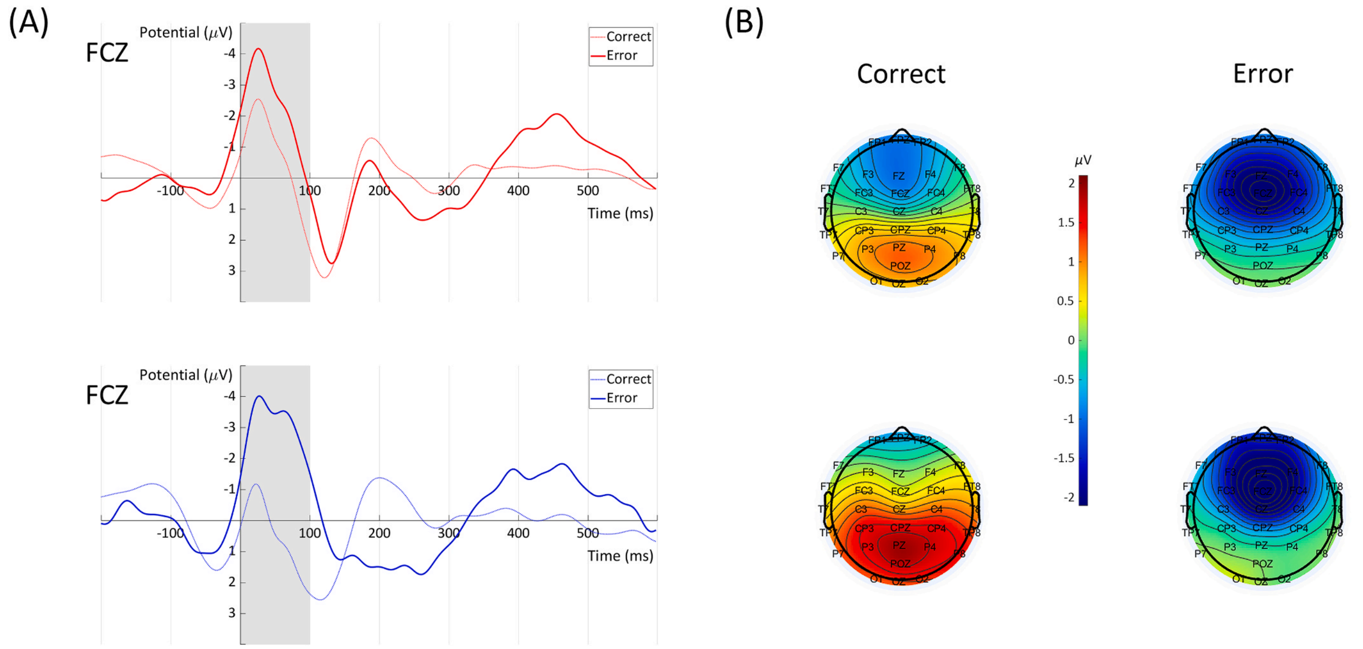

Fig. 2. (A) Raw grand averaged response-locked waveforms for correct and incorrect responses at FCz for the HMA (top) and the LMA (bottom) groups. Time 0 is response onset. The time windows for ERN/CRN is shaded. (B) Topographies of correct (left) and incorrect (right) responses in the 0–100 ms window for the HMA (top) and LMA (bottom) groups.

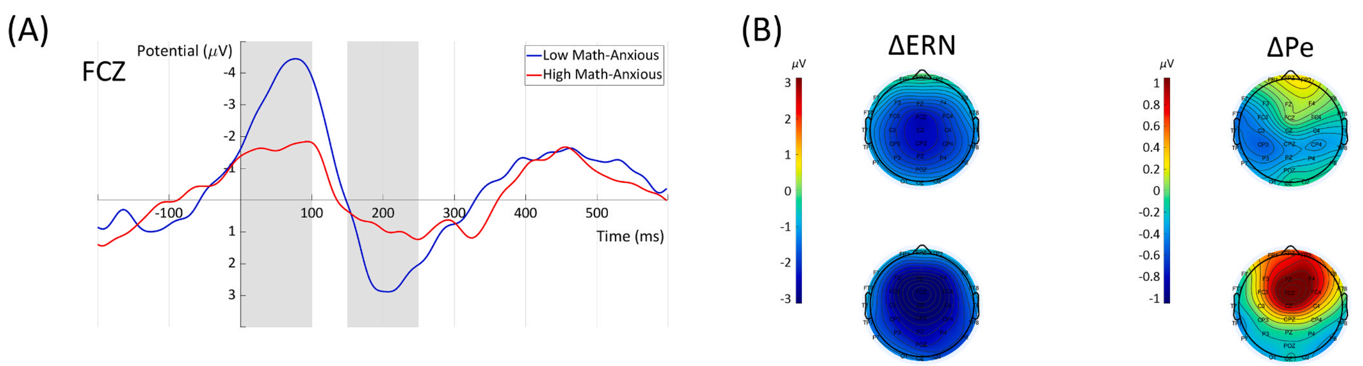

Fig. 3. (A) Difference waves (error minus correct response) for the LMA and HMA groups at FCz. Time windows for ΔERN and ΔPe are shaded. (B) Topographies of ΔERN and ΔPe in the 0–100 ms and 150–250 ms window, respectively, for the HMA (top) and LMA (bottom) groups.

Table 3
Means and standard errors of the means (SEM; in brackets) for ERN, CRN, ΔERN, Pe and ΔPe at FCz for the LMA and HMA groups.

	ERN	CRN	ΔERN	Pe	ΔPe
LMA	-2.97 (.65)	1.37 (.56)	-4.32 (.76)	1.65 (.50)	1.45 (.50)
HMA	-2.80 (.43)	-.33 (.32)	-2.47 (.52)	.040 (.33)	.06 (.33)

Table 4
Spearman correlation coefficients between ERP measures (ERN, CRN, ΔERN, Pe, and ΔPe) and performance and anxiety (math and trait) measures.

	RT	ACC	MA	TA	PES	PEA
ERN	.075	.118	.114	.090	-.201	.060
CRN	-.477 * *	.417 * *	-.406 * *	.099	-.022	-.055
ΔERN	.414 * *	-.219	.392 * *	-.041	-.211	.085
Pe	-.344 *	.376 *	-.415 * *	.091	.168	.069
ΔPe	-.293 *	.392 * *	-.305 *	.023	.244	-.024

Note. RT: response time; ACC: % hits; MA: math anxiety; TA: trait anxiety; * $p < .05$ two-tailed; * * $p < .01$ two-tailed

first time that these ERP measures have been studied in an arithmetic verification task. This task was used because it allowed us to study response monitoring in a better ecological context compared to the numerical Stroop task used in a previous study in the field of math anxiety (Suárez-Pellicioni et al., 2013).

As expected, the HMA group showed slower response time and more errors in the task than their LMA peers, reproducing the well-known negative relationship between math anxiety and math performance (e.g., Ashcraft & Ridley, 2005). Moreover, a longer response time after a previous error than after a previous correct response (i.e., PES) and a tendency for an increase in hit rate after a previous error (i.e., increase in PEA) were also reproduced, supporting the conflict monitoring account (Botvinick et al., 2001). This account states that a compensatory control mechanism is activated after an error to improve subsequent performance. However, no differences between groups were found in these two behavioral error adaptation measures, indicating that the compensatory mechanism to improve subsequent performance (e.g., Danielmeier & Ullsperger, 2011) is present in both highly and low math-anxious individuals. This result is consistent with the study by Suárez-Pellicioni et al. (2013), who found no relation between math anxiety and post-error adjustments in performance in a numerical Stroop task.

With regard to electrophysiological measures, we found a sharp negative deflection at FCz that peaked around 50 ms post-response when an error was committed, consistent with the morphology and topography of ERN. Importantly, this is the first time that ERN has been reported in an arithmetic verification task, extending previous studies showing the ERN after erroneous responses compared to correct ones (Falkenstein et al., 1991; Gehring et al., 1993). Note that this component has previously been reported in simpler attentional control tasks, such as Stroop (e.g., Holmes & Pizzagalli, 2008), Go/NoGo (e.g., Sheffers et al., 1996), and flanker tasks (e.g., Olvet & Hajcak, 2008).

ERN in the present study was elicited in both the HMA and the LMA group, suggesting that the groups do not differ in the evaluation of errors. This result contrasts with previous work by Suárez-Pellicioni et al. (2013), who found larger ERN for the HMA than for the LMA group in a numerical Stroop task. These authors interpreted their result using the motivational significance theory of ERN (Hajcak et al., 2005), suggesting the enhanced ERN in HMA individuals might reflect their greater sensitivity and concern over errors. There are several possible explanations of why between-groups differences in ERN amplitude were not found in the present study. Firstly, a different experimental task was used. Errors in an arithmetic task could be less salient for the HMA group than errors in a numerical Stroop task, because the former is more difficult for them than the latter. Although large ERNs have been associated with higher levels of anxiety in relatively simple speeded response tasks (e.g., Hajcak et al., 2003a), other studies using more complex tasks (e.g., reinforcement learning tasks or a random dot cinematogram task) have failed to find this relationship (e.g., Nieuwenhuis et al., 2005; Olvet & Hajcak, 2009c; Riesel et al., 2015). Significantly, even in simple tasks (e.g., flanker tasks), the association between ERN amplitude and anxiety/OCD/worry has not been always found. Some studies have shown that factors such as emphasizing speed or accuracy in task instructions (Riesel et al., 2019a,b), introducing trial-to-trial accuracy feedback (Olvet & Hajcak, 2009c) or, even, format presentation of stimuli (Lin et al., 2015) may alter this association. Thus, the present study adds further evidence of the controversial association between the ERN and anxiety.

A second explanation can be given for the absence of group differences in the ERN. The expectancy theory (Holroyd & Coles, 2002) claims that ERN is a marker of expectancy violation in which actual outcomes are compared to expected outcomes; thus, if the outcome is worse than expected, ERN is generated, but its amplitude decreases in expected outcomes. In this sense, the HMA group's low self-confidence in math (i.e., the belief in one's low competence and ability in mathematics; Ahmed et al., 2012) could have made them perceive their errors as more expected in the arithmetic verification task. However, math self-confidence was not measured in our study, and so further research is needed to explore the association between math self-confidence and ERN in mathematics tasks.

A third explanation for the lack of group differences in ERN in our study is that the state anxiety generated by the arithmetic task in the HMA group would make them reduce attentional allocation to the task and reduce the salience of their mistakes. This is the explanation that Moser et al. (2005) suggested for their observation that fear induction did not alter early error processing (i.e., ERN) when their spider-fearful participants performed a flanker task in the presence of a spider as compared with when they performed the task in its absence. The load on working memory generated by state anxiety could have limited the attentional resources devoted to the task. Previous studies have shown less negative ERN amplitudes when a secondary task reduces the attentional resources available in dual tasks (e.g., Pailing & Segalowitz, 2004).

In the present study, some interesting differences between groups emerged in other electrophysiological measures that we analyzed. Firstly, a larger ΔERN was found in the LMA group compared with their more anxious counterparts. It is noteworthy that this effect resulted from pronounced group differences in the CRN but not in the ERN amplitude: the HMA group showed greater CRN as compared with their LMA peers. Larger CRN amplitudes have previously been observed during tasks with high uncertainty regarding response accuracy (Endrass et al., 2008; Pailing & Segalowitz, 2004; Scheffers & Coles, 2000), so it has been suggested that it is related to conflict at the response level and/or is elicited by correct responses that are misjudged as errors. Thus, HMA individuals' larger CRN may be an indicator of their greater uncertainty about the accuracy of their answer. Moreover, in the present study, increased CRN amplitudes (i.e., larger negativities) were related to worse behavioral proficiency (i.e., slower response time and decreasing hit rate). The results of the present study extend those of previous research that showed that more difficult tasks produce larger CRNs (Compton et al., 2007) and that uncertainty about the correctness of one's own responses is associated with greater similarity in ERP activity for incorrect and correct responses, with reduced ERN for the former and enhanced CRN for the latter (Pailing & Segalowitz, 2004; Scheffers & Coles, 2000).

Our second electrophysiological result for group differences was that Pe and ΔPe were larger in LMA individuals as compared with their HMA peers. Previous findings suggested that Pe reflects awareness of and allocation of attention to mistakes (Hughes & Yeung, 2011; Nieuwenhuis et al., 2001; Steinhauser & Yeung, 2010). Moreover, Suárez-Pellicioni et al. (2013) found a reduction in the Pe amplitude for errors in a numerical Stroop task in the HMA group, which they attributed to individuals in this group not being fully aware of having made an error. Other studies have also reported smaller Pe in high-anxious individuals (e.g., Ghering et al., 2000; Hajcak & Simons, 2002), in those scoring high in negative affect (Hajcak et al., 2004) and in those with high levels of induced fear (Moser et al., 2005), which has been interpreted as less awareness of errors in anxious and affectively distressed individuals. Interestingly, Moser et al. (2011) reported that growth-minded individuals, who view failures as potentially instructive feedback and are more likely to learn from their mistakes (Dweck, 1999), showed enhancement of the Pe component compared with fixed-minded individuals (similar results were found for children in Schroder et al., 2017). They found this growth mind-set individuals' awareness of and attention to errors as early as 200 ms following error commission, but failed to find group differences in the initial reaction to failure (i.e., the ERN). Our results thus suggest that HMA individuals could be less certain that they have made a mistake and might not increase attention to subsequent errors. Thus, their likelihood of learning from mistakes in arithmetic tasks might decrease.

Finally, several findings are worth mentioning regarding the association between ERP and behavioral measures. First, our results are consistent with previous studies showing more negative CRNs related to slower and more error-prone responses (Files et al., 2021; Luu et al., 2000). This is consistent with a mechanism based on partial-error effects, where an erroneous response initiated but later corrected would result in a slower response time (Matsuhashi et al., 2021). Second, the more positive the Pe the faster and more accurate the responses, and thus more awareness of errors is related to better performance. As for behavioral post-response measures, contrary to previous studies, no relationship was found between ERN amplitude and either PES or PEA. However, there are multiple studies that found no such association (for a review, see Weinberg et al., 2012b). For example, Hajcak et al. (2003a) found that ERN magnitude was unrelated to PES and they found no relation between PES and worrying, either. Thus, our results add new evidence of no variation in ERN amplitude related to behavioral post-error adjustments to improve task performance.

The present study has two limitations that should be mentioned. Firstly, prior studies have reported a Pz maximum for the Pe component (e.g., Shalgi et al., 2009), but we found this component at the frontal and central electrodes. However, it should be noted that this frontocentral Pe has been described previously. Indeed, Ullsperger et al. (2014) described two positive deflections appearing after ERN: a frontocentral early Pe and a centroparietal slow wave, known as late Pe. The first is suggested to share the same neural generators as ERN, whereas parietal cortex and rostral ACC seem to contribute to late Pe. Further research should examine differences between these two positive components to clarify their role in error processing. Secondly, due to the negative association between math anxiety and math ability (Hembree, 1990), we cannot establish conclusively whether group differences in the present study are solely due to math anxiety.

Despite these limitations, the present data offer the first evidence about an altered response monitoring system in HMA individuals in arithmetic verification tasks. In particular, they could be less certain about the accuracy of their answer and less aware of their mistakes. Given that the monitoring of responses and adaptation to mistakes are key aspects for learning, these deficits could contribute to HMA individuals' low achievement and difficulties in math. Moreover, the present study provides evidence for the first time that response-related negativities are elicited in an arithmetic verification task, which allows us to study response-monitoring processes in a more ecological context than those previously used.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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