Abnormal numerical processing in math-anxious individuals: Evidence from event-related brain potentials

PhD thesis

Macarena Suárez Pellicioni

Universitat de Barcelona

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Abnormal numerical processing in math-anxious individuals: Evidence from event-related brain potentials

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Macarena Suárez Pellicioni

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Dr. María Isabel Núñez Peña

Dr. Àngels Colomé Gonzalez

Tutor

Dr. Elisabet Tuba Sala

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A mi madre y a mi abuela

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SUMMARY

This PhD thesis comprises five studies aiming to investigate differences between low math-anxious (LMA) and high math-anxious (HMA) individuals in numeric processing by means of behavioral and event-related potential (ERPs) measures. The excellent temporal resolution of the ERP technique was expected to provide detailed information that would shed light about the difficulties HMA individuals face when they have to deal with numbers.

The first study aimed to adapt into Spanish and validate the Shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989) as a starting point of this thesis, in order to make sure that the construct of math anxiety (MA) was going to be assessed with an instrument providing valid and reliable measures. The adaptation into Spanish of the sMARS scale gave sound evidence of its good psychometric properties: strong internal consistency, high 7-week test-retest reliability and good convergent/discriminant validity.

Study II aimed to investigate, with the ERP technique, the use of the plausibility strategy in math-anxious individuals by studying Faust et al. (1996)´s finding on *flawed scores* for dramatically incorrect solutions (*large-split*) in an arithmetic verification task. We were able to replicate, for the first time, those findings, by finding a greater percentage of *flawed scores* for *large-split* solutions for the HMA group as compared to the LMA one. Moreover, ERP analysis showed that *large-split* solutions generated a P600/P3b component of larger amplitude and delayed latency for the HMA group as compared to the LMA one. Given the functionality of this component, this finding suggested that *large-split* solutions demanded more cognitive resources and required more time to be processed for the HMA group than for the LMA one. These findings were interpreted according to the Attentional Control Theory (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007): HMA individuals, being more influenced by the stimulus-driven attentional system, would have succumbed to the distractor nature of the *large-split* solution, devoting more time (P600/P3b latency) and cognitive resources (P600/P3b amplitude) to process this clearly wrong solution, instead of using the plausibility strategy.

Study III consisted of finding the electrophysiological correlates of numeric interference in LMA and HMA individuals, by means of a numeric Stroop task. We found that HMA individuals needed more time to solve this task as compared to their LMA peers, suggesting that they were distracted by the task-irrelevant dimension of the stimuli (i.e. physical size of numbers). ERP data analysis showed that LMA and HMA individuals differed in the way they adapted to conflict: the LMA group presenting a greater N450 component for the interference effect preceded by congruence than

when preceded by incongruity while the HMA group showed the same enhancement but for the subsequent Conflict sustained potential. These results suggested that both groups showed a different implementation of attentional control, which was executed in a proactive way by LMA individuals and in a reactive way by HMA ones. A reactive recruitment of attentional control in HMA individuals would have made them more influenced by bottom-up input (i.e. stimulus-driven attentional system), making them more vulnerable to distraction.

The two remaining studies of this PhD thesis aimed to explore two possible factors contributing to the development of MA. Given that errors are crucial for mathematical learning, because of its cumulative nature, one concept building on the next, Study IV aimed to assess whether LMA and HMA individuals differed in the way they processed a numeric error as compared to a non-numeric one. We found that HMA individuals showed an increased *error-related negativity* (ERN) when they committed an error in the numeric Stroop task, but not in the classical Stroop task. Furthermore, standardized low resolution electromagnetic tomography (sLORETA) analysis showed significant greater voxel activation at the right insula for the errors committed in the numerical task as compared to the classical one for the HMA group and not differences at all for the LMA one. Given that the right insula has been associated with the discomfort with one´s own physiological responses and given that errors are considered to generate a cascade of physiological responses, this finding suggests that HMA individuals´ may have experienced a discomfort with the physiological responses generated by a numeric error. This negative bodily reaction towards numeric errors may be at the base of the development of negative attitudes towards mathematics and of the tendency of HMA individuals to avoid math-related situations.

Finally, Study V aimed to investigate, by means of an emotional Stroop task, whether MA is characterized by an attentional bias towards math-related information, given that an attentional bias towards threatening information is considered to be a contributory factor in the origin and maintenance of several types of anxiety. This study showed that HMA individuals showed a clear tendency of responding slower to math-related words as compared to neutral words. Given that this slowdown in an emotional Stroop task has traditionally been interpreted as an attentional bias towards threatening or emotional stimuli, this study demonstrates that MA is also characterized by an attentional bias, in this case, towards math-related words, which could probably be at the base of its development and maintenance.

To sum up, this PhD thesis has shown that MA is characterized by a vulnerability to distraction, which was shown when a *large-split* solution was presented for a simple addition task (Study II)

and when physical size interfered with numerical magnitude in a numeric Stroop task (Study III). Moreover, HMA individuals also showed a reactive recruitment of attentional control after conflict detection (Study III), a greater sensitivity or emotional response to numeric errors (Study IV) and a clear tendency of an attentional bias towards math-related stimuli (Study V).

ORIGINAL PUBLICATIONS

Study I:

Núñez-Peña, M.I., Suárez-Pellicioni, M., Guilera, G., and Mercadé, C. (2013). A Spanish version of the short Mathematics Anxiety Rating Scale (sMARS). *Learning and individual differences, 24*, 204-210.

Study II:

Suárez-Pellicioni, M., Núñez-Peña, M.I., and Colomé, A. (2013). Mathematical Anxiety Effects on Simple Arithmetic Processing Efficiency: An ERP study. *Biological Psychology, 94*, 517-526.

Study III:

Suárez-Pellicioni, M., Núñez-Peña, M.I., and Colomé, A. (2013). Reactive recruitment of attentional control in math anxiety: an ERP study of the numeric conflict monitoring and adaptation. *PLoS ONE*, *9*(6): e99579.

Study IV:

Suárez-Pellicioni, M., Núñez-Peña, M.I., and Colomé, A. (2014). Abnormal error monitoring in math-anxious individuals: Evidence from error-related brain potentials. *PLoS ONE*, *8*(11), e81143.

Study V:

Suárez-Pellicioni, M., Núñez-Peña, M.I., and Colomé, A. Attentional bias in high math-anxious individuals: Evidence from an emotional Stroop task (Under review in *Motivation and Emotion).*

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ABBREVIATIONS

ACC	Anterior cingulate cortex
ACT	Attentional control theory
CMM	Conflict monitoring model
CRN	Correct-related negativity
CSP	Conflict sustained potential
DLPFC	Dorsolateral prefrontal cortex
DMC	Dual mechanisms of control
ERN	Error-related negativity
ERPs	Event-related potentials
fMRI	Functional magnetic resonance imaging
HMA	High math-anxious
IFJ	Inferior frontal junction
LMA	Low math-anxious
LPC	Late positive component
LPFC	Lateral prefrontal cortex
MA	Math anxiety
MST	Motivational Significance theory
PET	Processing efficiency theory
RTs	Response times
sLORETA	Standardized low resolution electromagnetic tomography
sMARS	Shortened Mathematics Anxiety Rating Scale
WM	Working memory

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“Affect is the least investigated aspect of human problem solving,
yet it is probably the aspect most often mentioned as deserving further investigation“
(Mandler, 1989, p. 3).

INTRODUCTION

What is math anxiety?

“Anxiety is an omnibus construct and under its rubric there has appeared a host of subconstructs that relate to discrete situations” (Hembree, 1990, p.33). The subconstruct that relates to mathematics is called math anxiety (MA). It has been defined as “an irrational and impeditive dread of mathematics” (Lazarus, 1974, p. 551), “the panic, helplessness, paralysis and mental disorganization that arises among some people when they are required to solve a mathematical problem” (Tobias, 1978, p. 65), a “general fear of contact with mathematics” (Hembree, 1990, p. 45) or the “feeling of tension, apprehension or even dread, that interferes with the ordinary manipulation of numbers and the solving of mathematical problems” (Ashcraft & Faust, 1994, p. 98).

Gough, a teacher, was the first to use the term *mathemaphobia* to refer to this type of anxiety, as an attempt to explain why some of her students failed mathematics courses despite proficiency in other subjects (Gough, 1954). Some years later, Dreger and Aiken (1957) claimed that although emotional factors may disrupt mastery of mathematics, “almost no controlled research has been attempted in the realm of emotional problems associated with arithmetic and mathematics” (Dreger & Aiken, 1957, p. 344). To change this situation, they made the first attempt to introduce standardized assessment into the study of what they called *number anxiety* by adding three questions about emotional reactions towards math to the Taylor Manifest Anxiety Scale (e.g. “Many times when I see a math problem I just *freeze up*”; Taylor, 1953) and renaming it the *Numerical Anxiety Scale*. Despite this first attempt, the most prominent development in the field of MA was the publication, two decades later, of the Mathematics Anxiety Rating Scale (MARS) by Richardson and Suinn (1972), which provided the first formal instrument for measuring this construct. The MARS is a 98-item rating scale on which the respondents rate, on a 1 to 5 Likert scale, how anxious they would feel in situations ranging from formal math settings to informal everyday situations. After this initial scale, other descendants and shorter versions emerged, like the 25-item abbreviated version of the MARS (sMARS; Alexander & Martray, 1989), the 12-item Fennema-Sherman Mathematics Anxiety Scale (MAS; Fennema & Sherman, 1976), the 6-item Sandman Anxiety Towards Mathematics Scale (ATMS; Sandman, 1980), the 24-item Math Anxiety Rating Scale Revised (MARS-R; Plake & Parker, 1982), the 9-item Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003), etc. Despite the wide variety of scales in English, no scale had been adapted into Spanish nor validated for Spanish population. Thus, in order to investigate the topic of MA anxiety with Spanish population, we needed a test in Spanish that would be able to provide valid and reliable measurements of this construct. Consequently, the first objective and starting point of this thesis was to adapt the sMARS test into Spanish and to validate it for Spanish population.

Besides proposing the *Numerical Anxiety Scale*, Dreger and Aiken (1957) also hypothesized that MA was conceptually distinct from general anxiety. Some years later, Hembree (1990)´s meta-analysis corroborated this prediction by reporting a correlation of .38 between MA and trait anxiety, showing that, despite the fact that individuals who are high in MA also tend to score high on trait anxiety, these two types of anxieties are clearly separated. Moreover, MA has also been associated with test anxiety. In this respect, Dew, Galassi, and Galassi (1983) used different instruments to measure MA (MAS (Fennema & Sherman, 1976); ATMS (Sandman, 1980) and MARS (Richardson & Suinn, 1972)) and a measure of test anxiety (Spielberger Test Anxiety Inventory; Spielberger, 1977) in order to study the relationship between these two types of anxieties. They found that fully two thirds of the variance in MA was shared among different MA assessments and was unexplained by test anxiety. In the same line, Hunsley (1978)´s study, exploring the similarities and differences in the cognitive processes involved in math and test anxiety suggested that, in the context of mathematical examinations, MA had incremental validity in the prediction of many cognitive processes (e.g. subjective ratings of exam importance, post-exam performance estimations and ratings of performance satisfaction), which were related to MA but not to test anxiety. Finally, a posterior meta-analysis found a correlation of .52 between MA and test anxiety (Hembree, 1990), which, after corrected for attenuation, gave a coefficient of determination of only .37, showing that only 37 percent of one construct´s variance was predictable from the variance of the other. According to this evidence, researchers have claimed that “the two constructs do not seem to be interchangeable” (Dew et al., 1983, p. 446) or that “it seems unlikely that mathematics anxiety is purely restricted to testing” (Hembree, 1990, p. 45), MA deserving to be considered a separate construct.

Despite being a separate construct, MA is not acknowledged in the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV; American Psychiatric Association, 2000). However, it has been suggested that “unlike other topics taught throughout formal education, math appears to be the only specific topic that generates enough difficulty to be the object of a genuine phobia” (Ashcraft & Ridley, 2005, p. 324). Similarly, previous researchers have suggested that MA should be considered a genuine phobia because it fits its classical definition: it is a state anxiety reaction, it shows elevated cognitive and physiological arousal and it is a stimulus and situation-specific learned fear (Faust, 1992). In this sense, Faust (1992) found physiological evidence of increasing reactivity (i.e. changes in heart rate) when math-anxious individuals performed math tasks of increasing difficulty but not for an increasingly difficult verbal task, while no kind of reactivity emerged for the LMA group.

These physiological responses of HMA individuals might be in the basis of their negative attitudes towards this discipline. In this respect, Hembree (1990) found a negative correlation between MA and enjoyment of math (grades 5-12: -.75; college: -.47), self confidence in math (grades 6-11: -.82; college: -.65), self-concept in math (-.71), motivation in math (-.64), opinion about usefulness of math (-.37) and attitudes towards math teachers (-.46). Thus, the sum of MA and negative attitudes towards math might give as a result the avoidance of math-related situations and numeric contents (i.e. global avoidance). Putting it simple, "if one dislikes math and feels that one is poor at math, then one probably does not enroll in math beyond basic graduation requirements" (Ashcraft, Krause, & Hopko, 2007, p. 335). Similarly, LeFevre, Kulak, and Heymans (1992) constructed a regression model to predict students´ choices of university majors varying in mathematical content and found that whereas age, fluency in math and experience with math contributed significantly to the prediction, a "math affect" factor, composed of MA and avoidance measures, more than doubled the variance accounted for by the model. In this respect, Hembree (1990)'s meta-analysis showed that MA significantly correlated with the extent of enrollment in high school math (*r* = -.31), with the intent to enroll in college math (*r* = -.32) and with the number of high school math courses taken (*r* = -.45).

However, the effects of MA are not only restricted to academic contexts. For example, it has been shown that MA prevents consumers from computing prices accurately, leading them to prefer easier to process dollars-off price promotions (absolute discount; e.g. $10 off, regular price $50) than percentage-off formats (relative discount; e.g. 20% off, regular price $50), even when the latter implied a higher discount than the former (Suri, Monroe, & Koe, 2013). Similarly, a significant negative relationship has been found between levels of MA and self-efficacy in performing numerical and drug calculation in nursing students, the students who failed the numerical and drug calculation ability tests being more anxious and less confident in performing calculations than those who passed (McMullan, Jones, & Lea, 2012).

MA and numerical cognition

Until the 90’s, the research on MA was based on assessing MA’s relations with math attitudes, math achievement and other types of anxiety. In parallel to these research, several studies assessed the effect of arithmetical problems´ characteristics on performance, discovering some of the most fundamental effects in this discipline, like the *problem size effect* (i.e. RTs and errors increase as the size of the problems increases; Ashcraft & Battaglia, 1978) or the *split effect* (i.e. RTs and errors decrease as the proposed solution in an arithmetic verification task deviates more from the correct one; Ashcraft & Battaglia, 1978).

Nevertheless, it wasn´t until Ashcraft and Faust (1994)´s study that the research on MA and that on numerical cognition converged. Until that moment there were no evidences at all that, in fact, *there were* a relationship between mathematics anxiety and an individual´s processing of math problems (Ashcraft & Faust, 1994). To assess the existence of this relationship Ashcraft and Faust (1994) formed four groups according to participants´ level of MA and manipulated the complexity of the task by presenting four stimuli sets in a verification task: two simple sets including single-digit additions and multiplications and two complex sets including two-digit additions and mixed arithmetic operations. Their findings can be summarized in three main points.

First of all, they found that the four anxiety groups performed rather similarly in the simple addition and multiplication tasks, suggesting that the effects of MA on RTs is either very weak or inexistent in the overlearned simple arithmetic operations of addition and multiplication. On the contrary, complex additions and mixed arithmetic operations were challenging enough to make emerge the effects of MA. As a result, they proposed the *anxiety-complexity effect*, that is, a “deterioration of high anxious subjects´ performance when the stimulus conditions became more difficult or complex” (Faust, Ashcraft, & Fleck, 1996, p. 28). Second, they found that Group 4 (highest HMA) was frequently faster than Group 3 (middle HMA) and sometimes faster than Group 2 (middle LMA) but showed the highest error rates, suggesting that this group seemed to sacrifice accuracy for speed (i.e. *speed-accuracy trade off*). Finally, for complex additions, HMA groups took the same time to reject false carry problems regardless of where the incorrect value was located (units or decades’ columns), suggesting that they did not take advantage of the opportunity to self-terminate processing upon detecting the incorrect value, instead of using the short-cut employed by their LMA peers. They explained these two last findings as manifestations of two different types of avoidance: on the one hand, a *global avoidance effect*, (i.e. enrolling in fewer math courses or selecting college majors involving less math content), which would have made

HMA individuals be less trained on mathematics. Being less knowledgeable about mathematics, they would have been less keen to discover special strategies, thus failing in self-terminating processing when the incorrect value was presented in the units column. Moreover, Ashcraft and Faust (1994) claimed the existence of a *local avoidance effect*, reflected as the desire to complete the math task as soon as possible to leave the uncomfortable situation of math problem solving. This latter type of avoidance would be responsible for the *speed-accuracy trade off*, given that HMA individuals would have responded faster just to finish the math task as soon as possible.

Given that Ashcraft and Faust (1994) found that HMA individuals seemed not to use the self-terminating strategy when verifying false problems, Faust et al. (1996) aimed to further investigate this finding by studying the *split effect*, another well-known effect in mathematical cognition, which has been related to the use of different strategies. In this respect, *large-split* solutions in an arithmetic verification task, (when the proposed solution is far away from the correct one; e.g. 3 + 7 = 25) are considered to be solved by using a *plausibility strategy*, that is, by easily discarding the clearly incorrect solution without completing the regular calculation process. On the contrary, *small-split* solutions (i.e. when the proposed solution is very close to the correct one; e.g. 3 + 7 = 11), are considered to be solved by means of an *exhaustive verification strategy*, given that the exact calculation is necessary to give a response. Moreover, besides the classical measures of RTs and error rates, they created a new one, called *flawed scores,* which were computed as the combination of two scores: the proportion of errors and the proportion of extreme RTs scores. Since they “reflects both those difficulties that yielded an error as well as those that generated an inordinately slow RT” (Faust et al., 1996, p. 34), they were taken to show subjects´ difficulties in processing. Faust et al. (1996)’s results showed that the greatest effects of MA were shown for complex problems but not for simple ones, which gave support to Ashcraft and Faust (1994)’s *anxiety-complexity effect*. On the other hand, very interesting results emerged from the *split effect* analysis. They found that, while LMA individuals showed the expected result on *flawed scores* (i.e., higher for *small-split* solutions and reduced for the easiest *large-split* ones), the highest HMA group (group 4) showed a curious and unexpected pattern, generating more *flawed scores* as the level of split increased. In other words, the higher MA group showed a higher proportion of *flawed scores* as the proposed solution deviated more from the correct one, what generated a difference between math-anxious groups in the largest split solution, the one expected to be the easiest to discard for being clearly implausible. They interpreted this finding as probably showing “an overall difference in some decision or evaluation stage of performance on the part of highly anxious subjects” (Faust et al., 1996, p. 42). Despite the surprising nature of this finding and the vagueness of its explanation, it has never been replicated or studied in more depth. Consequently, the second objective of this thesis was to study this finding with the help of the ERP technique, in order to determine whether there is some difference between math-anxious groups when processing this implausible proposed solution. In this respect, ERPs are voltage fluctuations that are associated in time with some physical or mental occurrence. These potentials are recorded from the human scalp and extracted from the ongoing electroencephalogram (EEG) by means of filtering and signal averaging (Picton et al., 2000). This analysis gives as a result waveforms that plot the changes in voltage as a function of time. In this respect, the greatest advantage of this technique is its high temporal resolution, in the order of the milliseconds, reason why ERPs can accurately measure *when* processing activities take place in the human brain.

In this respect, a central-posterior distributed positive-going ERP component, called late positive component (LPC), is considered the electrophysiological correlate of the *split effect*. Evidence has suggested that this component is actually a member of the P300 family (Coulson, King, & Kutas, 2010), whose amplitude is taken as a measure of the amount of attentional resources allocated to the stimulus and whose latency is linked to the stimulus-related processing time. Comparing this component between groups would let us discover whether the HMA group devote more time and/or more cognitive resources to process this type of solution, what would let us know whether they do have a difficulty in processing dramatically incorrect solutions or whether Faust et al. (1996)’s *flawed scores* are not a useful measure for determining participants’ difficulties in processing.

MA and the role of working memory (WM)

Why do HMA individuals differ from their LMA peers only when complex arithmetic is involved? The initial researchers on the field of MA interpreted this *anxiety complexity effect* in the context of the Processing Efficiency Theory (PET; Eysenck & Calvo, 1992), one of the most important theories aiming to explain the relationship between anxiety and performance in cognitive tasks. According to the PET, anxiety reaction consists of intrusive thoughts and worries to which the individual pays attention (e.g. preoccupation with one´s dislike or fear of math, one´s low self-confidence, etc.), being this diversion of attentional resources to task-irrelevant thoughts what disrupts the high anxious individual´s performance by reducing the available pool of WM resources. Consequently, when an anxious individual performs a cognitive task, its level of performance will be degraded to the extent that it relies on WM resources. By extending this model to the field of MA, previous researchers had predicted that math performance would be disrupted among HMA individuals when the task demanded a significant involvement of WM (Ashcraft & Faust, 1994; Faust et al., 1996).

Nevertheless, this hypothesized relationship between MA and WM was not formally investigated until Ashcraft and Kirk (2001). In their first experiment, participants´ WM capacity was measured by requiring them to store an increasing number of words or digits in WM while processing simple verbal or arithmetic tasks. In the verbal task participants heard a number of simple sentences (e.g. "Last fall the farmers had a good harvest") and must answer a simple question (e.g. When?) and then recall the final word of each sentence (e.g. harvest), in serial order. In the numeric task, participants had to solve an arithmetic verification task (e.g. 5 + 2 = ?; 6 + 3 = ?) and then recall the last addends of each operation, in order (e.g. 2, 3). They carried out a correlational analysis and found that higher math anxiety was associated with lower WM span, but only for the arithmetic verification task, with almost no relationship between MA and language-based span. On a second experiment, participants were tested in a dual-task paradigm in which they were asked to hold a string of either 2 or 6 random letters in WM while solving an addition problem (involving carrying and non-carrying additions) and finally, to recall the letters presented in the first place. They found that when the memory load was heavy (i.e. six letters) errors increased substantially and especially for the addition problems requiring carrying. This pattern was apparent in all three groups but was especially dramatic in the highest math-anxious one. In contrast, when the WM load was light (i.e. two letters) and when there was no carrying involved error rates were quite low and very similar across the MA groups. As a whole, they concluded that higher levels of MA were related to lower available WM capacity, but not as a stable characteristic, but as a temporary reduction in processing capacity when their anxiety was aroused, which would depress levels of performance in any math task that relied substantially on WM. Thus, they proposed that MA would function like a dual-task procedure, causing degradation in primary task performance of any math or math-related tasks that relied on resources from WM.

A clarification: MA and the role of inhibition

At this point, we know that HMA individuals are considered to be affected by disruptive thoughts, which are taken to compete with the task for WM resources and to originate the drop in performance, but: why do HMA individuals pay attention to disruptive thoughts? Why are they more vulnerable to worrying thoughts and ruminations? Do HMA individuals experience more worrying thoughts and ruminations than LMA ones? Or are they less able to control these thoughts and thus, more negatively influenced by them? In this respect, given that anxiety has been linked to a greater vulnerability to distraction (Eysenck & Byrne, 1992), it is possible that HMA individuals show difficulties in inhibiting attention to this distracting internal thinking as compared to their LMA counterparts.

Two studies aimed to investigate HMA individuals’ vulnerability to distraction. First, Hopko, Ashcraft, Gute, Ruggiero, and Lewis (1998) presented paragraphs for oral reading to participants classified as low, medium or high math-anxious. Participants´ task consisted of reading out loud the italicized parts of paragraphs, which could be math related or neutral, trying to ignore the non-italicized parts of the text, which could be either words (experimental condition) or a string of Xs (control condition), embedded as distracters within the paragraph. Within the experimental condition, the non-italicized distracters could be neutral (i.e. unrelated to paragraph content) or math-related (i.e. math words that were also unrelated to paragraph content). After the reading, participants were asked some questions to assess the level of comprehension of the paragraph content. Hopko and collaborators found that all participants showed slower reading times when words (rather than Xs) were embedded in the text, but the increase in reading times was particularly strong for the HMA and middle math-anxious groups (Hopko et al., 1998). However, the additional time these groups took for reading the paragraphs was not spent on improving their memory (groups scored quite similarly in the comprehension test) but in reading the non-italicized parts of the text (which should be ignored), probably due to a failure in inhibiting attention to distractors. As a consequence, they suggested a modification of Ashcraft and colleagues’ account (based on Eysenck & Calvo, (1992)´s PET theory): Although preoccupation and worrying thoughts had been taken as the factor responsible for the reduction of WM resources and subsequent performance deficits, they suggested that “it is perhaps more accurate to implicate a failure to inhibit attention to these thoughts as the key to understand this relationship” (Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998, p. 352). Consequently, what separated LMA and HMA individuals may not be the experience of intrusive and worrisome thoughts *per se* but rather their efficiency in inhibiting attention to them.

Similarly, Hopko, Mcneil, Gleason, and Rabalais (2002) formed two groups as being extreme in MA (20% top and bottom of distribution) and administered them with a card version of the numeric Stroop task, in which participants were told to state the quantity of numeric and non-numeric (i.e. letter) stimuli (e.g. 222222, correct answer: 6). They found that the HMA group took significantly more time to respond to numeric than to non-numeric stimuli, while the LMA one showed no differences in this respect. They interpreted this finding as showing HMA individuals´ difficulty in the dual task of inhibiting attention to the magnitude conveyed by the numeric stimuli while simultaneously attending to their quantity, as compared to the LMA group.

In this respect, the third objective of this thesis was to study the electrophysiological correlate of the numeric interference in HMA individuals, by means of the ERP technique. In this respect, two main ERP components have been associated with conflict processing, that is, consistently identified in the incongruent minus congruent difference wave in Stroop tasks: the N450 and the subsequent Conflict sustained potential (CSP). The N450 is a negative-going component appearing from approximately 350 to 500 ms post-stimulus at fronto-central sites. It has been related to stimulus conflict processing (i.e. at the level of stimulus representation) rather than to response conflict processing (Szűcs & Soltész, 2012). It has been claimed that its neural generator is the anterior cingulate cortex (ACC) (West, 2003), supporting (given the functions attributed to this brain area) the suggestion that it reflects conflict detection (West, Jakubek, Wymbs, Perry, & Moore, 2005). This component is followed by the CSP, emerging at central sites roughly 500 ms after stimulus onset (Appelbaum, Meyerhoff, & Woldorff, 2009) and its neural sources have been located within the lateral prefrontal cortex (LPFC; West, 2003). Despite the cognitive processes underlying this component are not yet clear in the literature, it has been associated with general preparation (West, Bowry, & McConville, 2004) conflict resolution (West & Alain, 2000), response selection (West et al., 2005) and the execution of top-down control (Larson, Kaufman, & Perlstein, 2009). Given that both components show a greater amplitude when the level of conflict increases, they can provide very interesting information about how LMA and HMA individuals detect conflict (reflected in the N450) and about the cognitive processes that take place later, in order to overcome it (reflected in the CSP).

Moreover, beyond conflict monitoring, it would be interesting to study possible differences between math-anxious groups in the way they adapt to conflict (Gratton, Coles, & Donchin, 1992). In this respect, it has been suggested that the interference is higher following congruent trials than following incongruent trials, because the perception of incongruity triggers an up regulation in cognitive control that would decrease the level of interference of the following trial (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Consequently, by studying conflict adaptation in LMA and HMA individuals, we would be able to find possible differences in the execution of cognitive control to overcome conflict, especially since such differences have been reported for trait anxiety (Fales, Barch, Burgess, Schaefer, Mennin, Gray & Braver, 2008; Osinsky, Alexander, Gebhardt, & Hennig, 2010; Osinsky, Gebhardt, Alexander, & Hennig, 2012)

MA as a deficit in low level numerical processing

Heretofore, Ashcraft and colleagues´ explanation of why MA affects math performance was the prominent one. As explained earlier, this explanation is based on two main claims: First, the effects of MA are shown on complex levels of mathematics, but not on simple ones, because the former need more WM resources to be solved. Second, the negative effects of MA on performance are considered to be generated by worrying thoughts, which would consume the WM resources that otherwise would be devoted to task solving, reason why MA would affect performance only for tasks involving WM resources (i.e. complex level).

Within this context, Maloney, Risko, Ansari, and Fugelsang (2010) carried out an experiment to study the possibility that the complex math deficits in HMA individuals may arise due to deficits in low level numerical processing skills. To this aim, participants were tested in a visual enumeration task of squares' sets. Two distinct patterns of performance are considered to emerge in this kind of tasks: First, *subitizing*, which emerges when 1-4 elements have to be enumerated, and which is characterized by a fast and accurate performance, showing a small increase in RTs and typically no decrease in accuracy as the number of stimuli presented increases. Second, *counting* is used when more than 5 elements are presented, and is characterized by an increase in RTs and decrease in accuracy as the number of elements increases. Moreover, these two processes are considered to differentially tap WM, counting putting greater demands than subitizing (Tuholski, Engle, & Baylis, 2001). Maloney et al. (2010) found that HMA individuals did not differ in subitizing but performed significantly worse in the counting range, as compared to LMA ones. This finding argued against the complexity claim of Ashcraft and colleagues´ proposal, given that math-anxious groups differed in a task as simple as enumerating the quantity of stimuli presented (i.e. 5-9). On the contrary, differences between groups emerged only for the process considered to demand more WM resources (i.e. counting), what gave support to the second main claim of Ashcraft and colleagues' proposal. Moreover, Maloney et al. (2010) included participants' WM capacity (measured with a backwards digit span and a backwards letter span tasks) as a covariate and found that the *Group* x *Number* interaction was no longer significant, suggesting that groups differences in WM capacity were probably mediating the group effect in performance.

Consequently, Maloney et al. (2010) suggested that the effect of MA may be located at a lower-level deficit in numerical processing and that the anxiety-induced WM reduction would have a secondary role by serving to further exacerbate the effects of low-level deficits.

In a subsequent study, Maloney, Ansari, and Fugelsang (2011) tested the idea that MA is associated with a basic deficit in the representation of numerical magnitude by means of two numerical comparison tasks: one where participants had to compare a number with a standard (i.e. lower/higher than 5), and another in which they had to compare two digits presented simultaneously (i.e. 3 8; which is the largest?), considered to involve less WM resources (because there is no standard to keep in mind for comparison). In order to assess how precise the participant´s representation of numbers was, Maloney and collaborators analyzed the *numerical distance effect*, consisting of participants being faster and more accurate when the distance between the two numbers to be compared increases (e.g., it is easier to compare 2 vs 9 than to compare 6 vs 8). This effect is considered to reflect the relative overlap of numerical magnitude representations on a mental number line (Dehaene, 1997) and has been associated with variability in mathematical skills (Holloway & Ansari, 2009). Maloney and collaborators found that, for the two types of numerical comparison tasks, the effect of numerical distance on RTs was larger for HMA than for LMA individuals (i.e. HMA individuals needed more time as the distance between numbers was reduced, as compared to the LMA one). Thus, whilst in their previous studies they found an effect of MA in the very simple task of counting but with involvement of WM resources, in this latter study they found that the effects of MA were shown in the simple task of comparing single-digit numbers, whether it implied more (i.e. standard fix) or minimal (i.e. two-digit) WM resources. This finding challenged the second claim of the dominant Ashcraft and colleagues´ account and suggested that a less precise representation of numerical magnitude most likely plays a role on MA. Indeed, they claimed that a hybrid theory can best explain the phenomenon of MA: HMA individuals suffer from a low level numerical deficit that would be at the base of their difficulties with more complex mathematics. These math difficulties, in turn, would result in WM-demanding ruminations when they perform math tasks, which would exacerbate the initial difficulties they experienced.

Neuroanatomical regions associated with MA

The bulk of research on MA had used behavioral measures to test their hypothesis (i.e. RTs, error rates, *flawed scores*). Nevertheless, it has been suggested that “knowing about the neural regions that are active when high- and low- math-anxious individuals perform in a math task, especially in combination with parallel tests on nonmathematical stimuli, would be enormously useful" (Ashcraft & Ridley, 2005, p. 325). Following this suggestion, recent research has incorporated new techniques in order to obtain more sensitive measurements about the timing of math-related processes (i.e. ERPs) or about the brain areas involved on them (i.e. fMRI). The investigations carried out at the University of Chicago by Beilock's research group are a good example of this kind of research.

Lyons and Beilock (2012a) formed two groups according to participants´ level of MA and administered them with a mental arithmetic task and a control task (word-verification; matched in difficulty) during fMRI data acquisition. Before each set of problems, individuals were presented with a cue (i.e. a simple colored shape) which identified the upcoming task (either math or control). According to these researchers, this would allow them to separate the effects of math (i.e. performance in a math task) from the effects of anxiety (i.e. anticipation to a math related task). They found that HMA individuals performed more poorly on the math relative to the word condition (while the LMA group showed no differences between tasks), some HMA individuals showing greater differences between tasks than others (Lyons & Beilock, 2012a). Curiously, these differences were not correlated with the self-reported level of MA, so their study aimed to determine the neural areas that predicted variation in the math deficits exhibited by HMA individuals. They found that performance in the math task was predicted by neural activity in response to the cue (i.e. when anticipating the math task) in the network of inferior frontoparietal regions, and more concretely, the bilateral inferior frontal junction (IFJ), an area associated with cognitive control and reappraisal of negative emotional responses. Furthermore, the relation between these frontoparietal activity and HMA individuals´ deficits during math performance was fully mediated by subcortical regions (i.e. caudate, nucleus accumbens and hippocampus), structures related with motivational factors. They interpreted that some HMA individuals were able to overcome the attentional deficits that may have caused MA by ramping up control resources before the math task itself began. Thus, they concluded that the extent of HMA individuals´ deficits in mathematics can be predicted by how cognitive control resources are recruited before doing math and with motivational resources during math performance. On the other hand, as a result of a posterior analysis of their data, Lyons and Beilock (2012b) found that when participants anticipated an upcoming math task, the higher one´s MA, the greater the activity in the bilateral dorso-posterior insula, an area associated with visceral threat detection and with the experience of pain itself, while these areas showed no significant activation during math task performance (Lyons & Beilock, 2012b). The authors interpreted this finding as showing that the anticipation of a math task was perceived as a painful event in HMA´s brains.

Finally, Young, Wu, and Menon (2012) tested 46 seven-to-nine year-old students (23 LMA and 23 HMA) with fMRI while they performed an addition and subtraction verification task. They found that for those early ages, MA was associated with: 1) an hyperactivity of the right amygdala, a brain region associated with processing negative emotions and fearful stimuli, which was observed in conjunction with lower problem-solving accuracy; 2) an abnormal effective connectivity of the amygdala, which was shown as a greater effective connectivity with the ventromedial prefrontal cortex regions, an area related with regulation of negative emotions, and as a less effective connectivity with the posterior parietal cortex (e.g. intraparietal sulcus, superior parietal lobule and angular gyrus), important for mathematical processing; 3) HMA individuals showed a reduced activity in the posterior parietal and in the DLPFC, regions involved in mathematical reasoning and attentional control, respectively. The greater connectivity between the right amygdala and the ventromedial prefrontal cortex in HMA children was interpreted to facilitate compensatory mechanisms that allowed children with HMA to perform well, albeit at a lower level than LMA children.

To sum this up, the research on the brain structures related with numeric processing in LMA and HMA individuals show a clear picture: MA is related with a differential activation of brain areas involved in attentional control (i.e. DLPFC; IFJ) and emotional processing (i.e. amygdala; insula).

Origins and maintenance of MA

At this point, we have described the cognitive processes that have been found to be related to MA, the two main explanations for it and the evidence about the brain areas shown to be related with it. Nevertheless, a very important question remains to be answered: Why do young children develop MA? How is it maintained? To date, the majority of studies have focused on environmental exposure to failure in mathematics as a potential primary mechanism for MA development (Ashcraft et al., 2007; Bekdemir, 2010; Meece, Wigfield, & Eccles, 1990). In this respect, Ashcraft has noted that several of his participants reported that public embarrassment in math classes contributed to the development of their MA (Ashcraft, 2002). Similarly, Bekdemir (2010) found that in pre-service teachers, a meaningful difference was found in MA levels between those who reported the worse experiences in mathematics classroom and those without those experiences. This suggested that negative events associated with math (e.g. instructors´ hostile behavior, peer pressure, inadequacy of instructors, etc.) may be directly related to the origins of MA.

In relation to negative experiences with math, the role of teachers seems to be key. In this sense, Turner and collaborators (2002) claimed that students with teachers who convey a high demand for correctness but provide little cognitive or motivational support may feel “vulnerable to public displays of incompetence” (Turner et al., 2002, p. 101), what can constitute a risk factor in MA development. Another important aspect in this regard is teachers´ own level of MA and the effect this may have on students’ learning and performance. In this respect, a moderate negative correlation has been found between teachers’ level of MA and math teacher efficacy, showing that the pre-service teachers with the lowest degree of MA had the highest levels of math teacher efficacy (Swars, Daane, & Giesen, 2006). In the same line, Beilock, Gunderson, Ramirez, and Levine (2010) carried out an interesting study to investigate the effect of teachers´ level of MA on students´ math learning. To this aim, they assessed the level of MA of 17 first- and second-grade female teachers and the math achievement of their students at the beginning and at the end of the course. They also measured students´ beliefs about gender and academic success in mathematics and the extent to which they adhered to traditional gender stereotypes (e.g. boys are good at math and girls are good at reading). They found that while no significant relation was found at the beginning of the school year, by the end of it, the more anxious teachers were about math, the lower the math achievement in girls who confirmed traditional gender ability roles (i.e. believe that females are bad in math) (Beilock et al., 2010). They concluded that in early elementary school, teachers’ MA had negative consequences for girls´ math achievement by influencing her beliefs about who is good at math.

Moreover, a very recent study investigating the genetic and environmental factors contributing to MA on monozygotic and same-sex dizygotic twins found that the development of this anxiety may involve not only exposure to negative experiences with math, but also genetic risk factors (Wang et al., 2014). More concretely, they found that genetic factors accounted for roughly 40% of the variation in MA, with the remaining being accounted for by child-specific environmental factors. A more in-depth analysis showed that MA was influenced by the genetic and nonfamilial environmental risk factors associated with general anxiety and additional independent genetic influences associated with math-based problem solving. In other words, they claimed that genetic risks underlying poor math ability and general anxiety may predispose children to the development of MA.

Indeed, this is not the first time that low math ability is suggested as a factor contributing to the development of MA. In this respect, a study aiming to determine the causal ordering between MA and math achievement found, by means of a structural equation modelling, that prior low math achievement appeared to cause later high MA across the entire junior and senior high school grades, while prior high MA hardly caused later low math achievement (Ma & Xu, 2004). Similarly, Maloney et al. (2010; 2011) proposed that MA is related with a less precise representation of numerical magnitude, which in turn would compromise the development of higher level of mathematics. In this line, they claimed that "as a function of their difficulty with mathematics, people could develop MA" (Maloney et al., 2011, p. 15), suggesting that a deficit in numerical ability could be at the base of MA development. On the contrary, other researchers have claimed that there is no compelling evidence that poor performance causes MA, given that the relation of MA with IQ and math ability is small and special work to enhance student's competence failed to reduce their anxiety levels (Hembree, 1990).

Moreover, there are other factors that may influence MA development and that have never been studied before, like the role of error processing. We have mentioned several times all along this text that HMA individuals committed more errors in a given numerical task than their LMA peers, but what lies behind those errors? Although the ability to learn from mistakes and to use that knowledge to improve performance is basic in any kind of learning and especially in math learning, given its cumulative nature, error processing has never been studied before in MA. In this respect, studying it in HMA individuals (i.e. how they perceive their errors, how they respond or adjust to them, if they differ in the way they perceive a numeric error as compared to a non-numeric one, etc), would constitute a very rich source of information in order to determine a possible factor contributing to the development or maintenance of MA.

In fact, the study of this error processing with ERP measures constitutes the fourth objective of this thesis. In this respect, the ERP component associated with errors is called the *error-related negativity* (ERN) (Gehring, Coles, Meyer, & Donchin, 1990). It is a response-locked ERP component observed as a sharp negative deflection at fronto-central sites along the midline approximately 50-150 ms after an error is committed (Gehring, Goss, Coles, Meyer, & Donchin, 1993). Several evidences suggest that it is generated in the ACC, a region of the prefrontal cortex that is richly connected with both limbic and frontal regions (Bush, Luu, & Posner, 2000). The precise cognitive mechanisms that generate the ERN are under debate but the principal theories claim that it reflects the detection of a mismatch between the representation of the actual and intended responses (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991); conflict monitoring arising from multiple simultaneous active response tendencies (Yeung, Botvinick, & Cohen, 2004); a signal of events being worse than anticipated (Schultz, 2002); or a motivational or emotional response to errors (Hajcak & Foti, 2008). In fact, this last interpretation of the ERN constitutes the core of the Motivational Significance Theory (Hajcak & Foti, 2008), which claims that this component reflects more than cold cognitive information, showing motivational or emotional response to errors. This theory is the only one that explains individual differences between participants: the greater the ERN amplitude, the greater the importance given to an error, or the emotional response to it. Indeed, previous evidence has shown that the amplitude of the ERN is greater when the significance of an error was higher, for example, when being precise in a task was emphasized over being fast (Gehring et al., 1993), when an error implied a higher monetary loss or when they were committed during social evaluation (Kim, Iwaki, Uno, & Fujita, 2005). Similarly, an ERN component of greater amplitude has been shown in individuals with certain personality traits, characterized by increased sensitivity to errors and, specially, in different kind of anxious patients, like those affected by obsessive compulsive disorder (Gehring, Himle, & Nisenson, 2000) or generalized anxiety disorder (Weinberg, Olvet, Doreen & Hajcak, 2010) as well as for students scoring high on obsessive-compulsive and generalized anxiety measures (Hajcak & Simons, 2002; Hajcak, McDonald, & Simons, 2003). Consequently, given the sound evidence supporting the ERN as a measure of emotional response to errors, this component constitutes a very rich source of information in order to detect possible differences in the emotional responses to errors between math-anxious groups. Finally, the analysis of the correct-related negativity (CRN; Coles, Scheffers, & Holroyd, 2001), the counterpart of the ERN in correct trials, would let us determine whether differences between math-anxious groups are limited to errors or whether they extend also for correct responses (i.e. implying an abnormal response monitoring in general).

Finally, there is another factor that may contribute to the development of MA: attentional bias towards threatening information. This bias refers to differential attentional allocation towards threatening stimuli relative to neutral stimuli (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007; MacLeod, Mathews, & Tata, 1986). Biases in processing threat-related information have been assigned a prominent role in the etiology and maintenance of anxiety disorders (Mathews & MacLeod, 2002). In this respect, one of the main findings in attentional bias research is that this bias occurs in all anxiety disorders while this effect is typically not observed in non-anxious individuals (Bar-Haim et al., 2007). For example, it has been shown that attentional biases occur in generalized anxiety disorder (Bradley, Mogg, White, Groom, & de Bono, 1999), social phobia (Amir, Elias, Klumpp, & Przeworski, 2003), post-traumatic stress disorder (Bryant & Harvey, 1995), specific phobia (Öhman, Flykt, & Esteves, 2001), panic disorder (Buckley, Blanchard, & Hickling, 2002) and obsessive compulsive disorder (Cisler & Olatunji, 2010). Given this evidence, it is very probable that an attentional bias towards math-related information would be present in HMA individuals, and that this bias could play some role in the origin or maintenance of this type of anxiety. Attentional bias has been traditionally measured with the emotional Stroop task, which has shown to be a reliable and valid index of attentional bias (Williams, Mathews, & MacLeod, 1996). Based on the original color conflict effect described by Stroop (1935), the emotional version of this task involves the presentation of stimuli that are thought to result in involuntary semantic activation, that is, emotionally or threatening words in different ink colors, participants task being to report that ink color. The semantic activation primed by the word is thought to interfere with the primary task of reporting ink color. Thus, the latency to respond accurately is believed to be a measure of the extent to which the target has activated a subjectively meaningful semantic node. In these experiments, individuals usually take significantly longer to color-name words specific to their pathology or concerns as compared to neutral control words.

Despite the infancy of MA research, Hopko et al. (2002) carried out an experiment to test whether an emotional Stroop task would elicit behavioral responding in math-anxious individuals consistent with that observed among other anxious samples (e.g. McNally, Riemann, Louro, Lukach, & Kim, 1992). This study aimed to overcome some of the methodological weaknesses that may have prevented McLaughlin (1996) to found an increased in RTs to math-related words as compared to neutral ones for HMA individuals (i.e. the emotional Stroop effect). To this aim, they introduced two main changes to McLaughlin (1996)´s study: First, groups were formed to be extreme (top and bottom 20%), instead of using a split-half subject sample based on the mean MA score and second, the task was presented in a computer, instead of employing a card presentation, given that the former is considered to be a more powerful method to assess interference than the latter (MacLeod, 1991). Thus, each participant was presented with Stroop screens containing 100 words, randomly displayed in five different colors. However, despite their efforts in improving McLaughlin (1996)´s methodological limitations, they still found no significant effect in RTs (Hopko et al., 2002). They acknowledged that this might have been due to the type of math-related words they used (the same as McLaughlin, 1996), which may have been too abstract (e.g. polynomial, theorem) and, therefore, less familiar for HMA individuals. Moreover, there were other methodological limitations in this study, such as the fact that response latencies were calculated for the 100 words that appeared together on the same screen, while calculating RTs separately for each word would have been a more sensitive method of demonstrating Stroop-related effects. Although finding an attentional bias towards math-related information in HMA individuals would be very important, revealing a possible mechanism by which MA may originate, maintain or aggravate, no study, to date, has demonstrated it. Consequently, the objective of the last study comprised in this PhD thesis was to reproduce previous studies using the emotional Stroop task and introduce some improvements, in order to determine whether those researchers did not find an attentional bias in HMA individuals because this bias is not a characteristic of MA or whether it never emerged because it was not assessed or measured properly.

This PhD thesis

The study of MA is important for two main reasons. First, math is at the base of our society, given its increasing reliance on technology and current concerns over STEM (Science, Technology, Engineering and Math). Given this context, more and better employment opportunities are available for those who are well trained on math, that is, for those who have followed degrees involving math content. As noted earlier, MA is related with math avoidance: HMA individuals will not register in degrees including math, after high school. As a consequence, MA has negative consequences on the professional development, employment opportunities and even salary prospects for those who suffer from it. Second, MA is more prevalent than thought. The last PISA inform (Program for International Student Assessment, 2012) showed that 61% of 15 year-old students from OECD countries expressed concern at the prospect of getting bad grades in math, 30% reported feeling incapable and 31% feeling nervous when solving a math problem, 33% acknowledge to feel tense when solving math homework and 59% reported to be worried about the difficulty of math classes. Given these two reasons, the topic of MA deserves further research.

The research on MA started in the 50's, but did not study its consequences on numerical processing until the 90's. The research on this topic has shown convergent evidence, as well as divergent evidence that have not been clarified yet. For example, studies using fMRI agree in the fact that MA activates brain structures related with emotional processing in HMA individuals. On the contrary, other evidence, using standard behavioral measures, has led to formulate contradictory claims about the effects of MA. In this respect, while Ashcraft and collaborators hold that MA affects performance only when a high level of mathematics is involved, Maloney and collaborators claim that the negative effects of MA on performance could be seen even in the simple task of comparing single-digits numbers or counting squares. Moreover, HMA individuals seem not to use the same kind of strategies as their LMA counterparts, for example, the self-terminating strategy when an incorrect number was presented at the place of the units of the proposed solution or the plausibility strategy when a dramatically incorrect solution was proposed for a given addition. In this respect, a differential use of strategies in LMA and HMA individuals was claimed after observing group difference in *flawed scores* for *large-split* solutions, a finding that have never been replicated nor studied in more depth. Furthermore, there are different claims about where to place the problems faced by HMA individuals, with some researchers claiming that the problem is placed on worrying thoughts consuming attentional resources from the WM, originating the drop in performance (Ashcraft and collaborators); others claiming that the problem is that HMA individuals find it hard to inhibit attention to distracting information, so they are more influenced by those worrying thoughts than their LMA counterparts (Hopko and collaborators) and others claiming that the problem in HMA individuals is placed at a very basic level of numerical processing, such as the processing of numerical magnitudes (Maloney and collaborators). Finally, the studies on the possible factors contributing to the development of MA are scarce and basically limited to environmental factors (school, teachers, etc.). Thus, given that the exact etiology of MA remains unknown, no intervention programs can be designed to prevent its onset. In this respect, further research needs to be done in order to reveal other possible factors that may play a role in the origin of this type of anxiety.

In this context, the objective of this PhD thesis was to investigate the difficulties that HMA individuals face when processing numbers with classical behavioral measures, as done by the bulk of research on MA, and most importantly, introducing the use of ERP measures. Thus, the use of this technique would let us know whether, in fact, HMA individuals devote more resources or more time to process dramatically incorrect solutions, by analyzing the P600/P3b component. Moreover, by studying the ERN, and given that it is considered to reflect the motivational significance or emotional reaction to errors, we would be able to find out whether HMA individuals show a greater emotional response to numeric errors as compared to non-numeric ones, discovering a possible factor influencing their avoidance of mathematics. Moreover, although spatial resolution of the ERP technique is limited, multichannel recordings allows an estimation of the intracerebral location of these cerebral processes. Thus, by using the sLORETA technique for comparing LMA and HMA individuals' brains when processing a numeric and a non-numeric error, we would be able to find out whether those differences were located at some of the brain areas previously reported to be related with MA (e.g. amygdala, insula, DLPFC, IFJ, etc.). Finally, studying the N450 and the CSP would allow us to compare the math-anxious groups in the different stages of conflict processing in order to determine whether the differences emerge in an early stage of conflict detection (as shown by the N450) or in a later stage, related with the actions taken to overcome conflict (as shown by the CSP).

Research objectives

Study I

The objective of the first study was to adapt and assess the psychometric properties of the Spanish version of the Shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989). We chose this scale instead of the original 98-item Math Anxiety Rating Scale (MARS) because the sMARS, having only 25 items, is less time-demanding and easy to administer in classroom settings. Moreover, we decided to adapt the sMARS instead of other shorter tests (e.g. 24-item MARS-R; 12-item MAS; 9-item AMAS; 6-item ATMS) because the former has been the most frequently employed in the investigation of MA and because it comprises three MA dimensions (i.e. math test anxiety, numerical task anxiety and math course anxiety). The adaptation of this scale into Spanish constituted the starting point of this thesis given that it would result in an instrument providing with valid and reliable measures of MA in the Spanish population.

Study II

The objective of the second study was to reproduce the differences between math-anxious groups on *flawed scores* when processing *large-split* solutions, as found by previous studies (Faust, et al., 1996) and more importantly, to use ERPs to give an explanation to this finding. The fact that HMA individuals differed on these scores for the largest split solution, the one that was most implausible, suggests that they did not benefit from using a plausibility strategy. Indeed, previous evidence had already suggested that HMA individuals seemed not to take advantage of this kind of self-terminating strategies. We expected that the use of a more sensitive technique, such as ERPs, would allow us to give an explanation for this finding.

Study III

The objective was to study HMA individuals' susceptibility to distraction by means of a numeric Stroop task and using the ERP technique in order to investigate its psychophysiological correlates. We expected to find a greater interference in RTs for HMA individuals as compared to LMA ones, as previously found with a distracting reading task (Hopko et al., 1998) and with a counting version of the numeric Stroop task (Hopko et al., 2002). Moreover, the use of the ERP technique, with its excellent temporal resolution would allow an identification of the two main conflict-related ERP components appearing in Stroop tasks and thus, to further investigate whether MA is related to earlier conflict detection or to a later response-related stage of conflict processing. Moreover, conflict adaptation effects were also analyzed, given that they can give very interesting information regarding the regulation in cognitive control that is implemented after conflict detection, in order to overcome it.

Study IV

The objective was to study how math-anxious individuals respond to self-generated errors in a numeric and a non-numeric task by means of the ERP technique, given that an abnormal error monitoring can constitute a possible factor in the development and/or maintenance of MA. Specifically, we aimed to determine whether HMA individuals show an enhanced *error-related negativity* (ERN), as previously shown for other high anxious populations (e.g. Weinberg et al., 2010). Moreover, the brain activity associated with correct responses, the *correct-related negativity* (CRN), was compared between groups, in order to determine whether MA has to do with an abnormal error monitoring only (i.e. enhanced ERN) or with an abnormal response monitoring in general (i.e. enhancement of both the ERN and the CRN). Finally, we used sLORETA to look for differences in brain activation between tasks for each group.

Study V

The objective of this study was to investigate attentional bias towards math-related information in LMA and HMA individuals by means of an emotional Stroop task. Despite the infancy of research on MA, this attentional bias has been previously studied (Hopko et al., 2002; McLaughlin, 1996). Nevertheless, some methodological limitations may have prevented these researchers to find significant differences between word types or between groups. Thus, the aim of this study was to replicate those studies by overcoming those methodological problems. Given that attentional bias towards threatening information has been suggested to be a key factor in the development of anxiety (Mathews & MacLeod, 2002), it would be of great importance to investigate whether MA is also characterized by an attentional bias towards math-related information.

Study I

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A Spanish version of the short Mathematics Anxiety Rating Scale (sMARS)

M. Isabel Núñez-Peña [a,b,*], Macarena Suárez-Pellicioni [a,b], Georgina Guilera [a,b], Clara Mercadé-Carranza [a]

[a] *Department of Behavioral Sciences Methods, Faculty of Psychology, University of Barcelona, Passeig Vall d'Hebron, 171, Barcelona, Spain*
[b] *Institute for Brain, Cognition and Behavior (IR3C), University of Barcelona, Passeig Vall d'Hebron, 171, Barcelona, Spain*

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ABSTRACT

The aim of this study was to adapt and assess the psychometric properties of the Spanish version of the sMARS in terms of evidence of validity and reliability of scores. The sMARS was administered to 342 students and, in order to assess convergent and discriminant validity, several subsamples completed a series of related tests. The factorial structure of the sMARS was analyzed by means of a confirmatory factor analysis and results showed that the three-factor structure reported in the original test fits well with the data. Thus, three dimensions were established in the test: *math test*, *numerical task* and *math course anxiety*. The results of this study provide sound evidence that demonstrates the good psychometric properties of the scores of the Spanish version of the sMARS: strong internal consistency, high 7-week test–retest reliability and good convergent/discriminant validity were evident. Overall, this study provides an instrument that allows us to obtain valid and reliable math anxiety measurements. This instrument may be a useful tool for educators and psychologists interested in identifying individuals that may have a low level of math mastery because of their anxiety.

1. Introduction

Mathematics anxiety is defined as "feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations" (Richardson & Suinn, 1972, p. 551). Math anxiety has been demonstrated to have unfortunate consequences in terms of mastery of math. Math anxious individuals take fewer math courses, get lower grades in the classes they do take, and choose college majors that are less related to mathematics and the physical sciences than their low math anxiety counterparts (Ashcraft, Kirk, & Hopko, 2000). Moreover, higher mathematics anxiety consistently relates to negative attitudes toward mathematics, low enjoyment of mathematics and poor self-confidence in the subject. In a meta-analysis, Hembree (1990) reported a correlation of −.75 between math anxiety and enjoyment of math and a correlation of −.71 between math anxiety and self-confidence in math. Given that being able to manage numbers is essential in a modern society which demands a workforce well trained in technologies, mathematics anxiety has become a subject of increasing interest (Ashcraft, Krause, & Hopko, 2007; Ashcraft & Ridley, 2005). In this sense, it is especially important to develop instruments to measure math anxiety, not only for educational and clinical purposes, but also for researchers interested in investigating the cognitive consequences of mathematics anxiety.

Dreger and Aiken (1957) were the first to attempt to measure math anxiety. They added three math-related items to the Taylor Manifest Anxiety Scale (Taylor, 1953) and named it the Numerical Anxiety Scale. In 1972, Richardson and Suinn published a more complete instrument for measuring math anxiety, the Mathematics Anxiety Rating Scale (MARS). The MARS is a 98-item rating scale on which participants, using a 1 to 5 Likert-type scale, have to rate how anxious they would feel in situations involving numbers, ranging from formal math settings (e.g., opening a math textbook) to informal (everyday) situations (e.g., working out a restaurant bill they think was miscalculated). The score on the MARS is simply the sum of the ratings across all 98 items (range from 98 to 490). Due to the good psychometric properties of the MARS measurements (e.g., a 7-week test–retest reliability of .85 and an internal consistency reliability of .97, reported in the original paper by Richardson and Suinn), the MARS has been adapted into many other languages and has become one of the most widely used instruments for measuring math anxiety. Moreover, the reliability and validity of scale scores has been frequently demonstrated (Alexander & Cobb, 1989; Dew, Galassi, & Galassi, 1984; Plake & Parker, 1982; Sloan, Slane, Ashcraft, & Fleck, 1994). Strong support for the reliability of the MARS scores was reported by Capraro, Capraro, and Henson (2001), who found that, across 28 studies, the MARS yielded scores with a mean internal consistency of .91, and, across 7 studies, it yielded scores with a mean test–retest reliability of .84.

Since the pioneering study by Richardson and Suinn (1972), other instruments have been developed to measure math anxiety: the 12-item Fennema–Sherman Mathematics Anxiety Scale (MAS; Fennema & Sherman, 1976), the 6-item Sandman Anxiety Toward Mathematics Scale (ATMS; Sandman, 1980), the 24-item Math Anxiety Rating

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* Corresponding author at: Department of Behavioral Sciences Methods, Faculty of Psychology, University of Barcelona, Passeig Vall d'Hebron, 171, 08035 Barcelona, Spain. Tel.: +34 933125853; fax: +34 934021359.
E-mail address: inunez@ub.edu (M.I. Núñez-Peña).

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Scale — Revised (MARS-R; Plake & Parker, 1982), the 25-item Abbreviated Math Anxiety Rating Scale (sMARS; Alexander & Martray, 1989), the 9-item Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003) and the 23-item Mathematics Anxiety Scale — UK (MAS-UK; Hunt, Clark-Carter, & Sheffield, 2011). The main advantage of all these instruments is that they are shorter version, less time-demanding than the original MARS. Although many English version instruments are available to measure math anxiety, a Spanish version has not yet been created. This study was designed to address the issue by adapting the sMARS (Alexander & Martray, 1989) into Spanish. We decided to adapt this instrument for two reasons: (a) of the all mathematics anxiety tests, until now the sMARS has been the most frequently employed as a mathematics anxiety test in the literature, and (b) as indicated by the scale developers it is supposed to measure three math anxiety dimensions that are not available in other math anxiety tests. The sMARS is a 25-item scale which has been demonstrated to be an adequate alternative to the 98-item MARS (Alexander & Martray, 1989). The sMARS correlated .93 with the MARS and had a two-week test–retest reliability of .86. Factor analysis revealed three underlying factors in the sMARS: (a) *math test anxiety*, defined by 15 items that reflect apprehension about taking a test in mathematics or about receiving the results of mathematics tests; (b) *numerical task anxiety*, defined by 5 items that reflect anxiety about carrying out numerical operations; and (c) *math course anxiety*, defined by 5 items that reflect anxiety about math classes. Coefficient alpha was .96 for Factor I, .86 for Factor II, and .84 for Factor III.

The purpose of this study was to adapt and study the psychometric properties of the scores on a Spanish-language version of the sMARS for a university population. Specifically, we were interested in evaluating the following aspects: (a) factor structure, (b) corrected item–total correlations, (c) internal consistency, (d) 7-week temporal stability, and (e) convergent and discriminant validity. In order to study the relationship between the sMARS scores and other related measures, participants were administered a series of tests: the State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), three scales (Spatial Visualization, Reasoning Ability and Verbal Ability) from the Thurstone's Primary Mental Abilities Test (PMA; Thurstone, 1939), the Addition and Subtraction Verification Test from the French kit (French, Ekstrom, & Price, 1963), and a Single-digit Addition Test created by us for the present study. A short questionnaire to obtain information about participants' attitudes toward mathematics (degree of enjoyment, motivation and self-confidence in mathematics) was administered and information about their high-school itinerary[1] was also collected. Subjects had to indicate whether they had previously graduated from high school with a concentration in social science, humanities, technology, science or other. The first two itineraries have very little mathematical content, while the last two involve a great deal of mathematics and calculation.

According to previous studies, mostly integrated in Hembree's meta-analysis (1990), we expected the following results: (a) a moderate negative correlation between math anxiety and the scores in the Addition and Subtraction Verification Test from the French kit, which allows us to measure arithmetic performance in multi-digit additions and subtractions; (b) a low relation between math anxiety and the score in the Single-digit Addition Test, because according to Ashcraft and colleagues (Ashcraft & Faust, 1994; Ashcraft et al., 2000; Faust, Ashcraft, & Fleck, 1996) math anxiety has a low impact in simple additions performance; (c) moderate positive correlations between math anxiety and trait and state anxiety; (d) a moderate negative correlation between math anxiety and spatial ability; (e) a low correlation between math anxiety and reasoning ability[2]; (f) no relation between math anxiety and verbal ability; and (g) strong inverse correlations between math anxiety and the degree of enjoyment, motivation and self-confidence in mathematics. Finally, we expected females to have higher mathematics anxiety than males (Hembree, 1990; Hyde, Fennema, Ryan, Frost, & Hopp, 1990), and individuals who follow social science and humanities to have higher mathematics anxiety than those who course technology and science (LeFevre, Kulak, & Heymans, 1992).

2. Material and methods

2.1. Participants

The participants were 342 undergraduate students from the University of Barcelona (Spain) who completed the sMARS test as part of a voluntary class activity (women, $n = 261$, 76.31%; men, $n = 81$, 23.68%). The mean age was 20.79 years ($SD = 3.32$, range = 18–43) for women and 21.21 years ($SD = 2.64$, range = 19–32) for men. All participants were first and second year Bachelor students majoring in Psychology, and had previously graduated from high school with a concentration in social science (37.7%), science (27.3%), humanities (23.1%), technology (7.7%) or others (4.2%). Mean and standard deviation for age and sMARS scores for the sample disaggregated by gender and high-school itinerary as well as the percentage of sample for each category are shown in Table 1. Participants were recruited using opportunity sampling from various lectures and practice seminars. The retest sample consisted of an opportunity sample of 104 students of the original sample (women, $n = 84$, mean age = 20.70, $SD = 3.01$, range = 18–40; men, $n = 20$, mean age = 21.37, $SD = 2.96$, range = 19–28) who completed the sMARS seven weeks after the first administration in order to study test–retest reliability. All participants gave written consent after being informed of the purpose of the study.

Psychometric properties of sMARS scores were evaluated in four opportunity subsamples, all of them proceeding from the original one: Subsample 1 (women, $n = 148$, mean age = 20.82, $SD = 3.29$, range = 18–43; men, $n = 41$, mean age = 21.20, $SD = 2.51$, range = 19–28); Subsample 2 (women, $n = 36$, mean age = 19.53, $SD = 2.00$, range = 18–26; men, $n = 14$, mean age = 19.71, $SD = 0.72$, range = 19–21); Subsample 3 (women, $n = 21$, mean age = 21.52, $SD = 2.60$, range = 18–27; men, $n = 7$, mean age = 22.71, $SD = 1.70$, range = 21–25); Subsample 4 (women, $n = 18$, mean age = 20.39, $SD = 1.97$, range = 18–25; men, $n = 4$, mean age = 22.75, $SD = 6.23$, range = 19–32). The information collected in each subsample is described in the Instruments section.

2.2. Instruments

2.2.1. sMARS (Alexander & Martray, 1989)

The sMARS is a 25-item version of the Math Anxiety Rating Scale (MARS; Richardson & Suinn, 1972). This instrument measures anxiety by presenting 25 situations which may cause mathematical anxiety grouped into three factors: *math test*, *numerical task* and *math course anxiety*. Items are answered on a five-point Likert scale from 1 (no anxiety) to 5 (high anxiety). Since sMARS total score is obtained by summing each item rating, scores range between 25 and 125. The test was back-translated into Spanish in order to apply it to the local population (more detail is given in the Procedure section). SMARS measurements were collected from all the subsamples.

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[1] Itinerary refers to the concentration or area of interest during high-school studies ("Bachillerato" in Spanish), thus before enrolling in University. In the Spanish educational system, students graduate from high school with a concentration in one of the following areas: social science, science, humanities, technology or other.

[2] There is increasing agreement that intelligence testing can be usefully approached through tests of inductive reasoning, which is acknowledged as being a central element in intelligence (Boyle, 1987). Gustafsson (1988) has demonstrated that general ability (G), general fluid ability (Gf) and inductive reasoning ability (IR) are synonymous and he says we can measure essential aspects of "G" by measuring inductive reasoning abilities. Given that the reasoning ability subtest from the PMA measures inductive reasoning, we have taken it as a measure of intelligence. According to Hembree (1990), higher mathematics anxiety was slightly related to lower IQ levels.

Table 1
Mean and standard deviation (in brackets) for age and sMARS scores for the sample disaggregated by gender and high-school itinerary. Percentage of sample for each category is also provided.

		Social science	Science	Humanities	Technology	Others
Men	%	22.44%	22.53%	21.66%	40.00%	18.18%
	Age	21.71 (3.66)	20.44 (1.78)	21.08 (2.01)	20.00 (1.69)	22.02 (4.19)
	sMARS	67.18 (14.20)	54.13 (14.00)	68.92 (18.41)	50.75 (12.55)	68.50 (10.60)
Women	%	77.55%	77.46%	78.33%	60.00%	81.81%
	Age	19.92 (1.96)	20.15 (2.08)	21.17 (3.73)	21.08 (2.61)	23.89 (7.50)
	sMARS	67.50 (15.57)	61.80 (17.10)	73.85 (14.73)	47.33 (11.58)	74.11 (18.61)

2.2.2. Simple-arithmetic test

This test consisted of 165 single-digit addition problems with the form $a+b=$ organized in five columns. It was administered with a time limit of two minutes that was not known to the subjects. The test was made up of twenty-four different single-digit additions (operands between 2 and 9). No addition included the numbers 1 or 0 due to evidence suggesting that problems including this numbers as addends are solved via rules rather than retrieval (Ashcraft, 1982). Tie problems (e.g., $4+4$) were also excluded. The score for the test was the number of correctly solved additions. Data were collected from subsamples 1, 2 and 4.

2.2.3. Addition and subtraction verification test from the French kit (French et al., 1963)

This consists of a total of 60 two-operand additions and subtractions that have to be verified by saying whether a proposed result is correct or incorrect. Subjects are asked to verify as quickly and as accurately as possible during a 2-minute period. French kit data were collected from subsamples 2, 3 and 4.

2.2.4. STAI (Spielberger et al., 1983)

The STAI is a 40-item scale used to measure state (STAI-S) and trait (STAI-T) anxiety. Good to excellent internal consistency (Cronbach's alpha = .86–.95) and adequate test–retest reliability (State: $r=.71$–.76; Trait: $r=.75$–.86) has been reported (Spielberger et al., 1983). It includes 40 statements describing different emotions, 20 for each scale. Items are answered on a four-point Likert scale. In the STAI-S the answer options go from 0 (not at all) to 3 (very much) and subjects have to answer by taking into account how they feel “right now”. In the STAI-T the answer options go from 0 (rarely) to 3 (almost always) and subjects have to answer by taking into account how they feel “in general”. STAI measurements were collected from all the subsamples.

2.2.5. PMA (Thurstone, 1939)

This test includes five subtests, but only three of them were used in this study: Spatial Visualization (S), Reasoning ability (R) and Verbal Comprehension (V). In the S subtest subjects have to look at a first figure (model) and then search for it among different rotated figures presented as answer options. The R subtest consists of a sequence of alphabet letters that have been ordered according to a certain criterion. Finally, in the V subtest subjects have to choose a synonym for a given adjective. PMA measurements were only collected from subsamples 3 and 4 because the administration of PMA is time-consuming and we were unable to prolong the administration of the tests in some lectures.

2.2.6. Three-item questionnaire

Three additional questions about mathematical enjoyment (*How much do you enjoy mathematics*?), self-confidence (*How much are you self-confident in mathematics*?) and motivation (*How much motivation do you have towards mathematics*?) were presented on a five-point Likert scale from 1 (not at all) to 5 (very much). Answers to these questions were collected from subsamples 1, 2 and 4.

2.3. Procedure

The study began with the translation of the sMARS into Spanish (see Appendix 1). The process started with a preliminary Spanish version of the test, then this Spanish version was back-translated into English (English-2) by an English native, and finally another English native reviewed the two English versions of the test and the Spanish one. Both reviewers were North American, English teachers and had a high level of Spanish. We found a few discrepancies between the original English version and the English back-translation of the test in some items, and these were solved by consensus.

The questionnaires were administered in normal classroom settings. All participants were presented with the sMARS and different subsamples were presented with the other tests (subsample sizes are given in Table 4). A subsample of 103 students was tested again on the sMARS seven weeks after the first administration of the test.

2.4. Data analysis

The distribution of sMARS scores was evaluated obtaining means, standard deviations (*SD*), observed range and percentage of students with missing values for factor and total scores.

A confirmatory factor analysis of the sMARS scores was carried out using the unweighted least squares estimation method, since data did not meet the assumptions of multivariate normality. A three first-order factor model with intercorrelations between factors was conducted to explore the fit of the underlying structure suggested by Alexander and Martray (1989) formed by three factors labeled *math test anxiety*, *numerical task anxiety* and *math course anxiety*. Chi-square statistic (χ^2), goodness of fit index (GFI), adjusted goodness of fit index (AGFI), parsimony goodness of fit index (PGFI), normed fit index (NFI) and standardized root mean squared residual (SRMR) were reported, and the model's goodness-of-fit was evaluated following these criteria (Hu & Bentler, 1999; Jackson, Gillapsy, & Purc-Stephenson, 2009; Mulaik et al., 1989; Schumacker & Lomax, 2004): a) χ^2 $p>.05$; b) GFI, AGFI and NFI$\geq$.95; c) PGFI$\geq$.60; and d) SRMR$\leq$.08.

The reliability of the sMARS measures was examined with an assessment of internal consistency by means of Cronbach's alpha coefficient computation, obtaining corrected item–total correlations for the three subscales and the total score. Test–retest reliability was assessed with intra-class correlation coefficient (ICC) between the sMARS administered at the two different time points, under the two way mixed model.

In order to provide evidence of convergent and discriminant validity of sMARS scores as a measure of the construct of the mathematics anxiety level, the other measures previously described were related to sMARS responses using the Pearson correlation coefficient, and the Fisher's *Z* test was used to assess the difference between correlations (Steiger, 1980). Known groups were defined by gender and high-school itinerary in order to assess the ability of the sMARS scores to differentiate between groups, and their scores on the three subscales and the total sMARS were compared by using *t*-tests or analyses of variance (ANOVA) where appropriate. When the homogeneity of variance assumption underlying the usual ANOVA was not satisfied, the test statistic developed by Welch (1951) was used. In order to compare groups in terms of previously taken itinerary, post hoc comparisons were tested by using Tukey

Table 2
Distribution of scores and reliability coefficients for the sMARS.

Subscale	Mean	*SD*	Range	Missing (%)	Cronbach's alpha	Corrected item–total correlation (range)	ICC
Math test	46.42	11.37	15–73	1.8	.93	From .39 (item 10) to .83 (item 8)	.73
Numerical task	9.32	4.09	5–24	0.0	.88	From .40 (item 16) to .87 (item 18)	.56
Math course	9.32	4.06	5–25	1.5	.85	From .54 (item 21) to .73 (item 25)	.67
Total score	65.09	16.91	25–115	3.2	.94	From .32 (item 16) to .75 (item 8)	.72

(1953) or Games and Howell (1976) procedures (this last procedure was used when homogeneity of variance could not be assumed). The magnitude of these differences was assessed with standardized mean difference (*d*) computing the mean difference between the two groups divided by the pooled standard deviation.

Participants with missing data were not excluded from the sample (within each subsample, percentage of cases with missing values was very low and no patterns were observed) and analyses were carried out with the available information by means of SPSS version 17.0 and AMOS version 18.0, setting statistical significance at $\alpha = .05$.

3. Results

3.1. Distribution of scores

The descriptive statistics for subscale and total scores are shown in Table 2.

If the percentage of participants with the lowest score (no math anxiety) is very high then we have what is known as floor effect, which may indicate that the capacity of the sMARS to discriminate between levels of anxiety is questionable when the level of math anxiety is very low. In this study, the number of participants with the lowest possible score was 1 (0.3%), 85 (24.9%) and 60 (17.5%) respectively for *math test anxiety*, *numerical task anxiety* and *math course anxiety*. In the case of the sMARS total score, only one participant (0.3%) with the minimum score of 25 was observed. Regarding possible ceiling effects (consisting of seeing a high percentage of participants with the highest possible score), there was one student who got the maximum score in the *math course anxiety* subscale. However, it is worth knowing that the distribution of sMARS scores covered almost the total possible range, both in the subscales and the total scores.

The very low percentage of participants with missing data indicates that the feasibility and acceptability of the sMARS is satisfactory when applied to university students.

3.2. Factor structure

The results from the confirmatory factor analysis of the sMARS are shown in Table 3. The obtained fit indexes for the three first-order factor model were $\chi^2(272) = 841.169$ ($p < .05$), GFI = .969, AGFI = .963, PGFI = .811, NFI = .961 and SRMR = .080. With the exception of the χ^2 measure, which is sensible to sample size and χ^2 centrality (Byrne, 2010), these indices suggest that the model fits the data, thus confirming that the underlying structure of the sMARS is formed by three factors that assess *math test*, *numerical task* and *math course anxiety*. Standardized factor loadings were higher than .45, showing that all items are relevant in defining the corresponding domain. A strong relationship was observed between *math test anxiety* and *math course anxiety* ($r = .72$, $p < .001$). Similarly the correlation coefficient between *math test anxiety* and *numerical test anxiety* was .54 ($p < .001$), and between *numerical test anxiety* and *math course anxiety* .57 ($p < .001$).

3.3. Internal consistency and temporal stability

As shown in Table 2, Cronbach's alpha coefficients were .93 for *math test anxiety*, .88 for *numerical task anxiety* and .85 for *math course anxiety*, with the corresponding corrected item–total correlations greater than .35 in all items. In the case of the sMARS total score, Cronbach's alpha reached a value of .94, again with high corrected item–total correlations with the exception of item 16 (*Reading a cash register receipt after your purchase — Revisar el ticket de compra después de haber pagado*) where a correlation coefficient of .32 was observed. These results indicate that the sMARS scores present excellent internal consistency (Kline, 2000) when applied to a university student sample.

Regarding measure stability, the ICC value for the sMARS total score was .72, indicating that test–retest reliability after seven weeks is good, and subscale ICCs ranged from .56 for *numerical task anxiety* to .73 for *math test anxiety*, showing moderate to high values of test–retest reliability.

3.4. Relations with other variables

Relations between the sMARS and the other measures produced the correlations specified in Table 4. The directions and magnitudes of these correlations were as predicted and some merit special attention. First, math anxiety and math achievement, measured by the French kit verification test, showed a moderate negative correlation

Table 3
Factor loadings and fit indexes of the three first-order factor model.

Items	Math test	Numerical task	Math course
1	.756		
2	.542		
3	.733		
4	.684		
5	.685		
6	.703		
7	.729		
8	.829		
9	.758		
10	.482		
11	.647		
12	.500		
13	.731		
14	.772		
15	.662		
16		.452	
17		.800	
18		.877	
19		.849	
20		.890	
21			.544
22			.726
23			.792
24			.784
25			.801

Goodness-of-fit indexes	
χ^2	$\chi^2(272) = 841.169$ ($p < .05$)
GFI	.969
AGFI	.963
PGFI	.811
NFI	.961
SRMR	.080

Note. GFI: goodness-of-fit index; AGFI: adjusted goodness-of-fit index; PGFI: parsimony goodness-of-fit index; NFI: normed fit index; SRMR: standardized root mean squared residual.

Table 4
Correlations between the sMARS and the other measures.

Subscale	Verification test (French kit) ($n=96$)	Addition simple task ($n=262$)	STAI-S ($n=260$)	STAI-T ($n=260$)	PMA-S ($n=87$)	PMA-R ($n=87$)	PMA-V ($n=86$)	Enjoyment ($n=262$)	Self-confidence ($n=262$)	Motivation ($n=262$)
Math test	−.26**	−.13*	.43**	.36**	−.24*	−.19	−.05	−.49**	−.54**	−.46**
Numerical task	−.38**	−.13*	.37**	.27**	−.14	−.07	−.06	−.41**	−.38**	−.36**
Math course	−.29**	−.06	.35**	.27**	−.32**	−.15	−.21*	−.36**	−.37**	−.37**
Total score	−.32**	−.13*	.46**	.37**	−.26*	−.18	−.11	−.52**	−.54**	−.48**

Note. STAI: State-Trait Anxiety Inventory, -S: State, -T: Trait; PMA: Primary Mental Abilities Test, -S: Spatial Visualization, -R: Reasoning ability, -V: Verbal Comprehension.
** $p<.01$.
* $p<.05$.

($r=-.32$), which indicates that the higher the math anxiety the lower the achievement in multi-digit additions and subtractions. Similar negative correlations, ranging from $r=-.26$ to $r=-.38$, were found between the verification test and the three math anxiety subscale scores. Second, a very small negative correlation ($r=-.13$) was found between the single-digit addition task and the sMARS total scores, and the same correlation value was found when the single-digit addition scores were correlated with those of *math test* and *numerical task anxiety*. No relationship was found between simple addition task performance and *math course anxiety*. Third, state and trait anxiety was moderately related both to the sMARS total score ($r=.46$ for STAI-S and $r=.37$ for STAI-T) and to the three subscale scores (values ranged from $r=.27$ to $r=.43$): highly math-anxious individuals also tend to have high state and trait anxiety. Fourth, math anxiety measured by means of the total sMARS and the *math test* and *math course anxiety* subscales was negatively correlated with spatial ability (correlation values from $r=-.24$ to $r=-.32$); however, the correlation between *numerical task anxiety* and spatial ability was lower and non-significant. In order to study differences between these three correlations we conducted comparisons between two dependent correlations. This analysis showed that the three correlations were not statistically different (see Table 5). Fifth, no relation was found between verbal ability and the sMARS total score ($r=-.11$) and the *math test* and *numerical task anxiety* scores ($r=-.05$ and $r=.06$, respectively). However, verbal ability was negatively related to math course anxiety ($r=-.21$). Again, comparisons between correlations showed that they did not differ significantly (see Table 5). Finally, moderate to high negative correlations ranging between $r=-.36$ and $r=-.54$ were found between math anxiety scores and the degree of mathematical enjoyment, self-confidence and motivation.

When analyzing the sMARS scores by gender and high-school itinerary, the mean scores and standard deviations shown in Table 6 were observed. As expected, women showed higher levels of anxiety than men, and statistically significant differences were found in *math task anxiety* ($t(334)=2.470$, $p=.011$) and the total sMARS score ($t(329)=2.395$, $p=.017$). The magnitude of effects in the differences between men and women were low, i.e. $d=.33$, .20 and .14 respectively for the three sMARS subscales and .31 for total score.

Table 5
Comparisons between correlations.

Comparison	Z score	p value
$r_{MT,S}$–$r_{NT,S}$	−0.92	0.35
$r_{MT,S}$–$r_{MC,S}$	0.89	0.37
$r_{NT,S}$–$r_{MC,S}$	1.73	0.08
$r_{MT,V}$–$r_{NT,V}$	0.09	0.92
$r_{MT,V}$–$r_{MC,V}$	1.72	0.09
$r_{NT,V}$–$r_{MC,V}$	1.45	0.15

Note. MT: Math test anxiety, NTA: Number task anxiety, MCA: Math course anxiety, -S: Spatial Visualization subtest from the PMA, -V: Verbal Comprehension subtest from the PMA.

Regarding the itinerary, in all math anxiety scores itineraries were ordered from high to low level of anxiety as follows: humanities, social science, science and technology. Statistically significant differences were found for *math task anxiety* ($F(4,253)=11.325$, $p<.001$), *numerical task anxiety* (Welch's $F(4,52.9)=10.160$, $p<.001$) and *math course anxiety* (Welch's $F(4,53.3)=8.139$, $p<.001$), and also for the sMARS total score ($F(4,249)=12.264$, $p<.001$). Post-hoc comparisons showed the statistical significances specified in Table 7, with statistically significant comparisons in italics. It is worth highlighting that individuals that had chosen humanities showed higher levels of math anxiety (measured both in the sMARS total score and in the subscale scores) than individuals that had chosen science and technology. Higher levels of math anxiety were also found in individuals that had chosen a social science itinerary compared to those reported to have chosen the technological one. Interestingly, noteworthy effect sizes were found in: i) humanities vs. technology ($d=1.54$), social vs. technology ($d=1.29$) and technology vs. others ($d=-1.68$) for *math test anxiety*, ii) humanities vs. technology ($d=1.08$) and technology vs. others ($d=-1.21$) for *numerical task anxiety*, iii) humanities vs. technology ($d=0.89$) and technology vs. others ($d=-1.24$) for *math course anxiety*, and finally iv) humanities vs. technology ($d=1.62$), social vs. technology ($d=1.29$), science vs. others ($d=-0.85$) and technology vs. others ($d=-1.81$) for the sMARS total score.

4. Discussion

The aim of this study was to examine the psychometric properties of the scores on a Spanish-language version of the sMARS. Math anxiety has become a subject of increasing interest in educational and clinical settings because of its consequences in reducing mastery of math, and a Spanish test for measuring this construct had not yet been developed. We decided to adapt the sMARS (Alexander & Martray, 1989) into Spanish because this instrument has been widely used and good psychometric properties of its scores and interpretations have been demonstrated. Moreover, it includes three subscales that are not present in other math anxiety tests, enabling us to separate *math test*, *numerical task* and *math course anxiety*. To our knowledge this is the first time that the three sMARS subscales have been studied in more detail.

Confirmatory factor analysis provided evidence for the underlying structure of the sMARS proposed by Alexander and Martray (1989). Fit indexes of the three first-order factor model were excellent and factor loadings for the items on the three subscales were high, suggesting that the three dimensions established in the original sMARS (*math test*, *numerical task* and *math course anxiety*) were also evident in the Spanish version.

The measures of the Spanish version of the sMARS showed excellent internal consistency both for the three subscales (Cronbach's alpha coefficients ranged from .85 to .93 for the *math test*, *numeral task* and *math course anxiety* subscales) and for the sMARS total score (Cronbach's alpha coefficient = .94). These values are close to those reported by Alexander and Martray (1989) in the original test. Moreover, good 7-week test–retest reliability was also found

Table 6
sMARS scores (means and standard deviations) by gender and high-school itinerary.

	Gender			Itinerary					
Subscale	Women	Men	*n* (W/M)	Humanities	Social science	Science	Technology	Others	*n* (H/So/Sc/T/O)
Math test	47.28 (11.21)	43.52 (11.52)	259/77	50.82 (10.35)	47.51 (9.73)	43.41 (11.68)	34.7 (10.83)	52.40 (9.92)	60/97/71/20/10
Numerical task	9.51 (4.22)	8.69 (3.60)	261/81	10.98 (4.44)	9.77 (4.19)	8.24 (3.61)	6.65 (2.21)	10.73 (4.82)	60/98/71/20/11
Math course	9.46 (4.05)	8.88 (4.07)	256/81	11.00 (4.60)	10.07 (3.85)	8.42 (3.77)	7.35 (2.16)	11.00 (3.97)	58/96/71/20/11
Total score	66.31 (16.87)	61.08 (16.52)	254/77	72.78 (15.84)	67.41 (15.07)	60.07 (16.67)	48.70 (11.78)	74.30 (17.56)	58/95/71/20/11

Note. W: women; M: men; H: Humanities; So: Social science; Sc: Science; T: Technology; O: others.

for the complete sMARS scores and for the three subscales' scores, which provides evidence of the stability of the measures of the Spanish version of the sMARS.

Convergent validity evidence was also examined and the results were consistent with previous studies, most of them summarized in Hembree's meta-analysis (1990). High scores in the sMARS measurements were moderately related to low achievement in multi-digit additions and subtractions, but showed little relationship with achievement in single-digit additions — it is worth noting that although this little relationship was statistically significant, it accounts for only 1.7% of the variance (Rosenthal & Rosnow, 1984). Multi-digit problems are generally considered as “complex arithmetic” because they are usually solved by means of hard calculation procedures, whereas single-digit additions are considered “simple arithmetic” because most people rely on fast direct retrieval from memory to solve them (LeFevre, Sadesky, & Bisanz, 1996). Our result agrees with that reported by Ashcraft and Faust (1994), who found that in simple arithmetic problems there were no math anxiety differences (high and low math-anxious individuals performed at the ceiling), but the math anxiety effect became obvious in more complex problems. These results may explain why highly math-anxious students get lower grades in their math classes. High scores in the sMARS responses were also negatively related to attitudes toward mathematics, enjoyment of mathematics and self-confidence in one's ability to do mathematics.

Table 7
Post hoc comparisons between high-school itineraries.

Comparison	*p* Value	*d* Value	Comparison	*p* Value	*d* Value
Math task anxiety			Math course anxiety		
H vs. So	.315	0.33	H vs. So	.700	0.24
H vs. Sc	*.001*	0.67	H vs. Sc	*.008*	0.62
H vs. T	*<.001*	1.54	H vs. T	*<.001*	0.89
H vs. O	.992	−0.15	H vs. O	1.00	0.00
So vs. Sc	.095	0.39	So vs. Sc	*.049*	0.42
So vs. T	*<.001*	1.29	So vs. T	*.001*	0.73
So vs. O	.630	−0.50	So vs. O	.944	−0.26
Sc vs. T	*.011*	0.76	Sc vs. T	.486	0.31
Sc vs. O	.088	−0.78	Sc vs. O	.312	−0.68
T vs. O	*<.001*	−1.68	T vs. O	.086	−1.24
Numerical task anxiety			Total score		
H vs. So	.442	0.28	H vs. So	.239	0.35
H vs. Sc	*.002*	0.68	H vs. Sc	*<.001*	0.78
H vs. T	*<.001*	1.08	H vs. T	*<.001*	1.62
H vs. O	1.00	0.06	H vs. O	.999	−0.09
So vs. Sc	.085	0.39	So vs. Sc	*.025*	0.47
So vs. T	*<.001*	0.79	So vs. T	*<.001*	1.29
So vs. O	.967	−0.22	So vs. O	.673	−0.45
Sc vs. T	.124	0.47	Sc vs. T	*.035*	0.72
Sc vs. O	.501	−0.66	Sc vs. O	.056	−0.85
T vs. O	.119	−1.21	T vs. O	*<.001*	−1.81

Note. H: Humanities; So: Social science; Sc: Science; T: Technology; O: others.

As regards the relationship between math anxiety and other psychological constructs, the sMARS scores were only moderately related to trait and state anxiety. Although individuals with high math anxiety also tend to show high state and trait anxiety, the correlation between both measures ranged between .35 and .46 for STAI-S and .27 and .37 for STAI-T, which demonstrated that math anxiety is a similar but separate construct from state and trait anxiety (as predicted by Dreger & Aiken, 1957). A moderate negative relation between math anxiety and spatial ability was also found, which may be due to the widely confirmed fact that number representation involves a spatial component (Hubbard, Piazza, Pinel, & Dehaene, 2005; Priftis et al., 2008). Finally, math anxiety was not related to verbal ability nor was the reasoning ability, as predicted (see Hembree's meta-analysis, 1990).

Discriminant validity evidence was also investigated. In line with previous studies (Hembree, 1990; Hyde et al., 1990), we found that females scored higher on math anxiety than males. Moreover, individuals who stated they had followed technology or science high-school itineraries had lower mathematics anxiety than those who followed social science or humanities. This result is in accordance with the fact that high math anxiety is related to students' intentions to enroll in fewer math courses and take fewer elective math courses (Ashcraft et al., 2000; Hembree, 1990). This result would also explain why math anxiety is related to students' choices of a college major, with those with higher math anxiety avoiding majors and careers that require a considerable math background (LeFevre et al., 1992).

To conclude, the findings discussed here demonstrate that mathematics anxiety can be reliably and validly measured by the proposed Spanish version of the sMARS. Not only has the utility of the sMARS been demonstrated but also the effectiveness of the three subscales to measure *math test*, *numerical task* and *math course anxiety*. Strong reliability was evident both in terms of internal consistency and in a 7-week temporal stability and convergent and discriminant validity evidences were also clear for the subscales and the overall sMARS measurements. In summary, the present study provides a Spanish-language instrument for measuring math anxiety that may be a useful tool for educators and psychologists interested in identifying individuals that may have a low math achievement because of anxiety. Additionally, it may also be useful to researchers interested in studying the cognitive consequences of math anxiety.

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Appendix 1. Spanish version of the sMARS

Los ítems de este cuestionario se refieren a experiencias que pueden causar tensión o aprensión. Para cada ítem señala cuán ansioso/a te pondría cada una de ellas. Responde de forma rápida, pero asegúrate de pensar bien la respuesta. Es muy importante responder a todos los ítems.

	Nada	Muy poco	Algo	Bastante	Mucho
1. Estudiar para un examen de matemáticas.	1	2	3	4	5
2. Examinarme de matemáticas en las pruebas de acceso a la universidad.	1	2	3	4	5
3. Hacer un control de matemáticas.	1	2	3	4	5
4. Hacer el examen final de matemáticas.	1	2	3	4	5
5. Coger el libro de matemáticas para empezar a hacer los deberes.	1	2	3	4	5
6. Tener deberes con muchos problemas difíciles que han de entregarse en la próxima clase.	1	2	3	4	5
7. Pensar en el examen de matemáticas que tendré dentro de 1 semana.	1	2	3	4	5
8. Pensar en el examen de matemáticas que tendré en 1 día.	1	2	3	4	5
9. Pensar en el examen de matemáticas que tendré en 1 hora.	1	2	3	4	5
10. Darme cuenta de que se debe hacer un cierto número de clases de matemáticas para cumplir con los requisitos académicos.	1	2	3	4	5
11. Coger un libro de matemáticas para comenzar una lectura difícil que se me ha pedido.	1	2	3	4	5
12. Recibir por e-mail la nota final de matemáticas.	1	2	3	4	5
13. Abrir un libro de matemáticas o de estadística y ver una página llena de problemas.	1	2	3	4	5
14. Prepararme para estudiar para un examen de matemáticas.	1	2	3	4	5
15. Tener que hacer un examen sorpresa de matemáticas.	1	2	3	4	5
16. Revisar el ticket de compra después de haber pagado.	1	2	3	4	5
17. Que me den una serie de problemas numéricos que incluyan sumas para que los resuelva con papel y lápiz.	1	2	3	4	5
18. Que me den a resolver una serie de restas.	1	2	3	4	5
19. Que me den a resolver una serie de multiplicaciones.	1	2	3	4	5
20. Que me den a resolver una serie de divisiones.	1	2	3	4	5
21. Comprar un libro de matemáticas.	1	2	3	4	5
22. Ver al profesor resolviendo una ecuación algebraica en la pizarra.	1	2	3	4	5
23. Matricularme en un curso de matemáticas.	1	2	3	4	5
24. Escuchar a otro alumno que explica una fórmula matemática.	1	2	3	4	5
25. Entrar en una clase de matemáticas.	1	2	3	4	5

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Study II

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Mathematical anxiety effects on simple arithmetic processing efficiency: An event-related potential study

M. Suárez-Pellicioni[a,b], M.I. Núñez-Peña[a,b,*], A. Colomé[b,c]

[a] Department of Behavioural Sciences Methods, Faculty of Psychology, University of Barcelona, Spain
[b] Institute for Brain, Cognition and Behaviour (IR3C), University of Barcelona, Spain
[c] Department of Basic Psychology, Faculty of Psychology, University of Barcelona, Spain

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ABSTRACT

This study uses event-related brain potentials to investigate the difficulties that high math anxious individuals face when processing dramatically incorrect solutions to simple arithmetical problems. To this end, thirteen high math-anxious (HMA) and thirteen low math-anxious (LMA) individuals were presented with simple addition problems in a verification task. The proposed solution could be correct, incorrect but very close to the correct one (small-split), or dramatically incorrect (large-split). The two groups did not differ in mathematical ability or trait anxiety. We reproduced previous results for flawed scores suggesting HMA difficulties in processing large-split solutions. Moreover, large-split solutions elicited a late positive component (P600/P3b) which was more enhanced and delayed in the HMA group. Our study proposes that the pattern of flawed scores found by previous studies (and that we replicate) has to do with HMA individuals'difficulties in inhibiting an extended processing of irrelevant information (large-split solutions).

1. Introduction

Mathematics anxiety is defined as "the panic, helplessness, paralysis and mental disorganization that arises among some people when they are required to solve a mathematical problem" (Tobías & Weissbrod, 1980, p. 65). High math-anxious individuals tend to espouse negative attitudes toward math and hold negative self-perceptions about their math abilities (Ashcraft, 2002). A meta-analysis conducted by Hembree (1990) concluded that in the college population math anxiety shows strong negative correlations with enjoyment of math (−.47), self-confidence in math (−.65) and motivation in math (−.64). Moreover, it is widely asserted that math anxiety is a major contributor to what Ashcraft and Faust (1994) called global avoidance, namely the documented tendency of math-anxious individuals to avoid situations that are math-intensive, leading them to avoid educational pathways and career avenues that depend on the discipline (Ashcraft & Ridley, 2005). An obvious but unfortunate consequence of all this is that high math-anxious individuals are at a disadvantage when competence or mastery is assessed with standardized tests, which is the reason for the negative correlation between math anxiety and math achievement (−.31) in the college population (Hembree, 1990). Given the importance of mathematics for academic and professional development (Bynner & Parsons, 1997) and the poorer perspectives for those students suffering from math anxiety, the topic is attracting increasing interest and is now considered a social problem that merits serious attention, in terms of both assessment and intervention.

Many studies have focused on the cognitive consequences of mathematical anxiety. While several authors have shown that high math-anxious (HMA) individuals perform worse than their low math-anxious (LMA) peers on a wide range of arithmetical tasks (Ashcraft & Kirk, 2001; Ashcraft & Moore, 2009), others have suggested that HMA and LMA individuals do not differ equally on all tasks of this kind. Ashcraft and Faust (1994) coined the term *anxiety–complexity effect* to reflect the fact that HMA individuals performed the same as their LMA counterparts on simple arithmetic problems, but that their performance deteriorated when the stimulus conditions become more difficult or complex. In a subsequent study, Faust, Ashcraft, and Fleck (1996) tested this anxiety–complexity effect by manipulating the *split*, i.e., the numerical distance between the proposed and the correct solution in a problem verification task (Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981). More specifically, the split effect consists of a slower and less accurate response when the proposed solution is a number

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[*] Corresponding author at: Department of Behavioural Sciences Methods, Faculty of Psychology, University of Barcelona, Passeig Vall d'Hebron, 171, 08035 Barcelona, Spain. Tel.: +34 93 312 58 53; fax: +34 93 402 13 59.
E-mail addresses: msuarezpellic@ub.edu (M. Suárez-Pellicioni), inunez@ub.edu (M.I. Núñez-Peña).

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close to the correct solution (e.g., 4 + 7 = 12; hereinafter, small-split solution) than when a dramatically incorrect alternative is proposed (e.g., 4 + 7 = 25; hereinafter, large-split solution) (Núñez-Peña & Escera, 2007).

The split effect has been associated with the use of different strategies. When a small-split solution is given, individuals are expected to use an exhaustive verification strategy to achieve the exact solution of the operation and give a response. However, when a large-split solution is given, individuals may respond by using a plausibility strategy, which is easier and quicker than doing the whole calculation for such an obviously incorrect solution (Duverne & Lemaire, 2005; El Yagoubi, Lemaire, & Besson, 2003, 2005; Núñez-Peña & Escera, 2007). To study the effects of math anxiety on the split effect, Faust et al. (1996) formed four groups according to their subjects' level of math anxiety. Individuals had to perform an addition verification task involving simple and complex (multi-digit) additions in the form $a + b = c$. Simple addition problems consisted of one-digit additions with addends between 0 and 9, and four different split solutions were presented: ±1, ±5, ±9 and ±23 (with the proposed solution always being positive). To analyze what they coined "subjects' difficulties in processing", flawed scores[1] were computed by adding the proportion of error trials to the proportion of trials with extreme response times (outliers). According to the evidence on strategy selection, individuals would be expected to solve the large-split solution by using a plausibility strategy and, consequently, have a low level of flawed scores, whereas small-split solutions should be solved by an exhaustive verification strategy and, consequently, be associated with a higher level of flawed scores. However, Faust et al. (1996) found an unexpected pattern of flawed scores across the split levels in HMA individuals: in the large-split condition (±23), where the incorrect solution was dramatically wrong, HMA individuals generated as high flawed scores as they did in the split-1 condition. Thus, a difference was created between groups in a split level in which, given the simplicity of the task, no differences were expected. This curious finding, which nobody has tried to replicate since, constitutes the core of the present study.

Previous research studying the electrophysiological correlate of the split effect has reported a late positive component (LPC) every time an arithmetic rule is broken (i.e., an incorrect solution is proposed for a given problem) (Niedeggen & Rösler, 1999; Núñez-Peña & Escera, 2007). The LPC is a central-posterior distributed positive-going event-related brain potential (ERP) component that starts around 500 ms and generally extends up to at least 800 ms. In fact, a component of equal polarity, topography and latency (labeled P600) has been described in other types of violation: orthographic (mis-spelled words) (Münte, Heinze, Matzke, Wieringa, & Johannes, 1998), syntactic (Osterhout, Holcomb, & Swinney, 1994), musical (Patel, Gibson, Ratner, Besson, & Holcomb, 1998) and violations in non-linguistic abstract sequences (Besson & Macar, 1987; Lelekov-Boissard & Dominey, 2002).

Cognitive neuroscientists familiar with the attention and decision-making literature will see similarities between the LPC/P600 and one of the earliest known ERP components, the P300. Previous authors have suggested that the late positivity time-locked to syntactic irregularity is actually a member of the P300 family (Coulson, King, & Kutas, 2010). The most commonly studied component in this family may be the P3b, considered to be sensitive to cognitive aspects of processing and whose amplitude is taken as a measure of the amount of attentional resources allocated to the stimulus. Although P3b amplitude becomes smaller as task difficulty or complexity exceeds attention resources, moderate increases in task demands well within the subject's capabilities should increase it, as the subject devotes more resources to the task (Salisbury, Rutherford, Shenton, & McCarley, 2001). On the other hand, P3b latency is linked to the stimulus evaluation time, or more generally, to the speed of cognitive processing of the stimulus. It has been suggested that by measuring P3b latency researchers can break down the overtly observable response time into two portions, one stimulus-related and one response-related, with variations in P3b latency reflecting stimulus processing independently of response-level processing (Verleger, 1997).

Previous studies have reported P600/P3b differences in amplitude and latency in different samples of anxious subjects. P600/P3b amplitude enhancements were found in post-traumatic stress disorder (Kimble, Kaloupek, Kaufman, & Deldin, 2000), in post-traumatic syndrome (Alberti, Sarchielli, Mazzotta, & Gallai, 2001), and in panic disorder (Pauli et al., 1997) while amplitude reductions have also been reported for subjects suffering from generalized anxiety disorder (Boudarene, 1998; Boudarene & Timsit-Berthier, 1997). On the other hand, P600/P3b latency differences have also been found in several anxious samples (Miltner et al., 2005; Schucard, McCabe, & Szymanski, 2008). For example, shorter latencies have been reported for high trait-anxious participants (Rossignol, Philippot, Douilliez, Crommelinck, & Campanella, 2005) and post-traumatic stress disorder patients (Matthew et al., 2001), while delayed latencies have been found in panic disorder (Turan et al., 2002) and obsessive-compulsive disorder (Papageorgious & Rabavilas, 2003) patients.

Several studies exploring anxiety-related effects have given support to the attentional control theory (Eysenck, Derakshan, Santos, & Calvo, 2007; hereinafter, ACT). This theory, an extension of the processing efficiency theory (Eysenck & Calvo, 1992), distinguishes between *performance effectiveness* and *processing efficiency*. While the former refers to the quality of performance, the latter refers to the relationship between the effectiveness of performance and the amount of resources or effort that has to be used to attain a given performance level. The main point of this theory is that anxiety affects processing efficiency to a greater extent than performance effectiveness, which implies that high anxious individuals, despite showing the same performance level as their low anxious counterparts, make inefficient use of the cognitive resources (using auxiliary processing resources/making a greater effort) in order to succeed in the task. In this line, according to the ACT, anxiety impairs processing efficiency because it reduces attentional control, a key function of the central executive. More specifically, the ACT assumes that there are two attentional systems: a *goal-directed attentional system*, influenced by expectations, knowledge and current goals (top-down control of attention) and a *stimulus-driven attentional system* responding maximally to salient or conspicuous stimuli (bottom-up control of attention) (Corbetta & Shulman, 2002). According to the ACT, anxiety decreases the influence of the goal-directed attentional system, and increases the influence of the stimulus-driven attentional system. This imbalance has direct negative consequences in the inhibition and shifting functions. The shifting function involves the ability to shift back and forth between multiple tasks, operations, or mental sets (Miyake et al., 2000). Several studies have suggested impaired task-switching performance and impaired performance on secondary tasks in dual-task situations in high anxious individuals (Ansari et al., 2008; Derakshan, Smyth, & Eysenck, 2009). On the other hand, the inhibition function involves using attentional control to resist disruption or interference from task-irrelevant stimuli or responses. High anxious individuals generally attend to salient or conspicuous stimuli because these stimuli command attention

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[1] Flawed scores are a measure created by Faust et al. (1996) to analyze subjects' difficulties in processing. Combining the proportion of errors and the proportion of extreme reaction time scores, this measure was expected to be sensitive to the subject's difficulties in processing, since it reflects both those difficulties that yielded an error and those that generated an inordinately slow reaction time.

from the stimulus-driven attentional system (Corbetta & Shulman, 2002), and they are therefore more easily distracted than low anxious individuals. Furthermore, the ACT suggests that the negative effects of anxiety on performance will be greater when overall processing demands are high and anxious individuals have insufficient processing capacity to regain attentional control.

Several studies of anxiety which have interpreted their results according to the ACT have taken the participants' level of accuracy on the task as a measure of performance effectiveness (how well or badly the task was performed) while reaction time has been taken as an index of processing efficiency (the more time expended achieving a given level of performance, the lower the processing efficiency) (Ansari et al., 2008; Basten, Stelzen, & Fieback, 2012; Eysenck et al., 2007; Williams, Vickers, & Rodrigues, 2002). Nevertheless, other studies have suggested that reaction time should not be considered a measure of processing efficiency, because it is another measure of how the task was performed (i.e., how fast), and thus, it measures the outcome of a processing rather than the processing itself (Basten et al., 2012). Other techniques such as ERPs or fMRI which assess brain activity during task performance can provide a more reliable measure of processing efficiency. Thus, neuroimaging evidence is taken as a measurement of processing efficiency, and reaction time and error rates as a measure of performance effectiveness. In fact, several studies investigating the effects of anxiety have found differences only when neuroimaging techniques were used but not with behavioral measures (Ansari & Derakshan, 2011; Basten et al., 2012; Fales et al., 2008). The explanation for these findings has to do with the fact that anxiety seems to be characterized by an abnormal recruitment of neural resources, and standard behavioral measures often provide very indirect evidence of internal processes. Previous evidence suggests that high anxious individuals differ in the amount of processing resources they expend on solving a given task, but not in their level of performance (Ansari & Derakshan, 2011; Eysenck & Calvo, 1992). Consequently, it is highly likely that HMA and LMA individuals will differ in terms of the cognitive resources they expend on solving the task. For this reason, in the present study ERP measures were registered in order to look for a possible electrophysiological correlate of Faust et al.'s (1996) flawed scores results, such as possible differences in resource investment, which would help us explain this unexpected finding.

With this objective in mind, we formed two groups which had extreme levels of mathematical anxiety, but which did not differ either in mathematical ability or in trait anxiety. The fact that mathematical ability was controlled for is significant, since the negative correlation between math anxiety and math achievement has prevented previous studies from discerning whether low performance was due to high anxiety or to a lower level of math ability. The fact that our individuals did not differ in terms of trait anxiety suggests that group differences will not be explained by differences in general anxiety.

Participants were presented with an addition verification task in the form $a + b = c$, involving addends between 2 and 9. The proposed solution could be correct, small-split (differing ±1 from the correct answer) or large-split (differing +14 from the correct one). We expected to find ERP differences between groups in the large-split condition because of previous evidence suggesting that high math-anxious individuals find it difficult to process large-split solutions (Faust et al., 1996).

To sum up, our predictions were as follows: (a) we expected to reproduce Faust et al.'s (1996) flawed scores results, i.e., that the HMA group would show a higher level of flawed scores in the large-split condition than the LMA group; (b) given that the groups did not differ in mathematical ability, and since, according to the ACT, anxiety affects processing efficiency to a greater extent than performance effectiveness, we did not expect any differences in reaction time or error rates[2]; (c) given previous evidence of a P600/P3b every time an arithmetic rule is broken (Niedeggen & Rösler, 1999; Núñez-Peña & Escera, 2007), we expected to observe this component in both the LMA and HMA groups when the proposed solution being verified was wrong. Nevertheless, given that processing difficulties were previously found in HMA individuals only for large-split solutions (flawed scores pattern), it was only in this condition that we expected to find amplitude and/or latency differences between groups that might be indicative of processing differences.

2. Methods

2.1. Participants

Participants were 26 healthy volunteers, half of whom had a high level of math anxiety and half a low level. They were selected from a sample of 342 university students who were assessed on math anxiety, simple mathematical ability and other psychological constructs (see Section 2.2).

The LMA group comprised thirteen participants (ten women; age range 18–25 years, mean = 20.1, SD = 1.9, twelve right-handed) who scored below the first quartile on the Shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989) (score range 37–53, mean = 45.6, SD = 4.7). The HMA group comprised thirteen participants (nine women; age range 18–32, mean = 23.0, SD = 4.1, twelve right-handed) who scored above the third quartile on the sMARS (score range 78–115, mean = 89.0, SD = 10.0).

In order to form the groups, individuals were paired off according to their scores on a simple arithmetic test and on the sMARS. Each pair of subjects had the same score on the arithmetic test but differed in mathematical anxiety, for which they both had an extreme score. We thus formed groups that differed only in mathematical anxiety ($t(24) = 14.09$, $p < .001$) and not in arithmetic ability ($t(24) = .18$, $p = .85$). Neither did the groups differ in trait anxiety ($t(23) = 1.159$, $p = .25$), spatial visualization ($t(24) = .71$, $p = .48$), reasoning ability ($t(24) = 1.02$, $p = .31$), verbal comprehension ability ($t(24) = .33$, $p = .74$), or gender distribution ($\chi^2 = 0.16$, $p = .68$).

Participants were paid for their participation and gave written informed consent before the experiment. All had normal or corrected-to-normal visual acuity and none of them reported any history of neurological or psychiatric disorder. The whole procedure was approved by the Ethical Committee of the University of Barcelona, and performed in accordance with the declaration of Helsinki.

2.2. Materials

Participants responded to the following tests.

2.2.1. Shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989)

The sMARS is a 25-item version of the Math Anxiety Rating Scale (MARS; Richardson & Suinn, 1972). This instrument measures the phenomenon by asking about 25 situations which may cause mathematical anxiety. Items are answered on a five-point Likert scale, from 1 (no anxiety) to 5 (high anxiety). The possible total score therefore ranges from 25 to 125. This test was adapted in order to make it applicable to a Spanish population (Cronbach's $\alpha = .94$, 7-week test-retest reliability = .72) (Núñez-Peña, Suárez-Pellicioni, Guilera, & Mercadé-Carranza, 2013).

2.2.2. Simple arithmetic test

This test consists of 165 single-digit addition problems of the form "a + b =" organized into five columns. There were twenty-four different additions involving operands between 2 and 9. No addition included the numbers 1 or 0 due to evidence suggesting that problems involving these numbers as addends are solved via rules rather than retrieval (Ashcraft, 1982). Tie problems (i.e., 4 + 4) were also excluded. Subjects were instructed to respond column by column, in order and as fast as possible. Given the simplicity of the task we established a time limit of two minutes in order to avoid a ceiling effect. Individuals were instructed to solve the additions as fast and as accurately as possible, but they were not told about the time limit because there is evidence suggesting that anxiety does not affect the measurement

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[2] Performance effectiveness has frequently been measured by error rates and response times (Ansari, Derakshan, & Richards, 2008; Basten et al., 2012; Eysenck et al., 2007; Williams et al., 2002). On the other hand, flawed scores, as the result of adding two behavioral measures (proportion of errors and extreme RT values) would also be considered as a measure of performance effectiveness. Nevertheless, this measure was created to detect difficulties in processing, and previous evidence suggests that they do differ in math anxiety (Faust et al., 1996). For this reason, although we expected no differences in reaction time or error rates (classical measures of performance effectiveness), we expected to replicate Faust et al.'s (1996) findings on flawed scores and find a higher level of this score for the HMA group.

of arithmetic performance when the task is performed without time pressure (Faust et al., 1996).

2.2.3. State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983)

Only the trait anxiety subtest was used. This includes 20 statements describing different emotions. Items are answered on a four-point Likert scale, with options ranging from 0 (almost never) to 3 (almost always). Subjects have to answer by considering how they feel 'in general'. Good to excellent internal consistency (Cronbach's alpha = .89–.96) and adequate 30-day test-retest reliability ($r = .75$) have been reported with high-school students (Spielberger et al., 1983).

2.2.4. Primary mental abilities test (PMA; Thurstone, 1939)

Three subtests of the PMA were used: spatial visualization (S factor), reasoning ability (R factor) and verbal comprehension (V factor). The S factor measures the ability to mentally manipulate and visualize geometric relations. In this subtest the participant's task consists in mentally rotating the proposed figures in order to choose those that are equal to an initial model. The R factor aims to measure the ability to find rules or principles in test items. It consists of a sequence of alphabet letters that have been ordered according to a certain criterion: individuals are expected to discover this criterion and choose the letter that completes the sequence. Finally, the V subtest measures vocabulary knowledge. In this case, individuals have to choose a synonym for a given adjective from four answer options.

At least three weeks separated the administration of the tests and the experimental ERP session, except for the PMA test, which was administered in the recording session. At the ERP session, participants were presented with the same additions used to assess their simple arithmetic ability when forming the groups, but on this occasion the additions were presented as a verification task in the form $a + b = c$, rather than as a production task. The manipulated variable was the type of proposed solution, which could be: correct (e.g., 6 + 7 = 13), incorrect with a small-split (±1 from the correct solution, e.g., 6 + 7 = 14) or incorrect with a large-split (+14 from the correct solution, e.g., 7 + 8 = 29). The proposed solution was never the product of a × b, the aim being to avoid the cross-operation confusion effect (Lemaire, Fayol, & Abdi, 1991).

The experiment was controlled by the E-prime 2.0 program (Psychology Software Tools Inc., Sharpsburg, PA, USA). Numbers were presented in white against a black background and subtended a visual angle of 1.48° vertically and either 1.03° (for one digit stimuli) or 2.40° (for two digit stimuli) horizontally.

2.3. Procedure

Participants were tested individually. Upon entering the experiment room they completed standard procedures regarding informed consent and were administered the spatial visualization (S), reasoning ability (R) and verbal comprehension (V) subscales of the PMA (Thurstone, 1939). Individuals were then seated 100 cm away from a computer screen in an electrically shielded, sound-attenuating recording chamber. The experimental session began with a training period consisting in the presentation of a series of trials selected from the same material that would be presented at the recording session. The training period consisted of a minimum of 18 trials and a maximum of 54 (to avoid fatigue). After each trial, individuals received feedback on their answer. Training finished when the participant had correctly answered at least 80% of trials. As the training trials were only used to familiarize the subject with the task, these trials were excluded from the statistical analysis. When the training period was over, the recording period started. During the recording period, individuals no longer received any feedback about their answers. The participant's task consisted in deciding the correctness of the proposed solution by pressing the left or right button of the mouse with their thumb (one for each hand). Half of the participants were instructed to press the left button when shown a *correct solution* and the right button when it was an *incorrect solution*, whereas the other half were instructed to do the opposite.

All participants were presented with 432 simple additions, 144 per type of solution (correct, split ±1 and split +14). Trials were organized into six blocks of 72 trials separated by a one-minute rest period and were randomly presented within each block, with the restriction that no more than three additions with the same type of solution could be presented consecutively.

Trials began with a 500 ms display of a fixation sign (an asterisk). After the fixation, the first addend was displayed for 1000 ms, followed by a 300 ms display of the sign +, a 1200 ms display of the second addend, and then the proposed solution, which remained visible until the subject had responded or for a maximum of 2000 ms. An inter-stimulus interval of 100 ms was left between each of these elements. Fig. 1 shows the sequential presentation of stimuli and their timing.

Individuals were instructed to respond as fast and as accurately as possible and were encouraged to keep their eyes focused on the screen and to refrain from blinking, except during the initial fixation period or until a rest message appeared on the screen.

2.4. Electrophysiological recording

The EEG was recorded using the ANT hardware and software (B.V., Enschede, The Netherlands) and with 31 electrodes mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH. ANT Advanced Neuro Technology). Five electrodes were placed over midline sites at locations Fpz, Fz, Cz, Pz and Oz, together with eight lateral electrode pairs over standard sites in frontal (FP1/FP2, F7/F8, F3/F4), central (C3/C4), temporal (T7/T8), parietal (P3/P4, P7/P8) and occipital (O1/O2) positions. Ten electrodes were placed halfway between the following additional locations: fronto-central (FC1/FC2, FC5/FC6), centro-parietal (CP1/CP2, CP5/CP6) and mastoid (M1/M2). EEG channels were continuously digitized at a rate of 500 Hz by an ANT amplifier (B.V., Enschede, The Netherlands). A band-pass filter was set from 0.5 to 30 Hz, and electrode impedance was kept below 5 kΩ. A 100-ms window prior to the presentation of the stimulus (−100 to 0 ms) served as the baseline. The horizontal and vertical electrooculogram was recorded with electrodes placed at the outer canthus and below the right eye, respectively. The common reference electrode was placed on the tip of the nose and ground was located on an equidistant point between Fpz and Fz. Trials with voltages exceeding 20 standard deviations in the EOG electrodes and ± 100 µV in the remaining electrodes were excluded from the ERP average. Ocular artifacts were identified and corrected with the eye-movement correction algorithm used in the EEprobe program (ANT, The Netherlands).

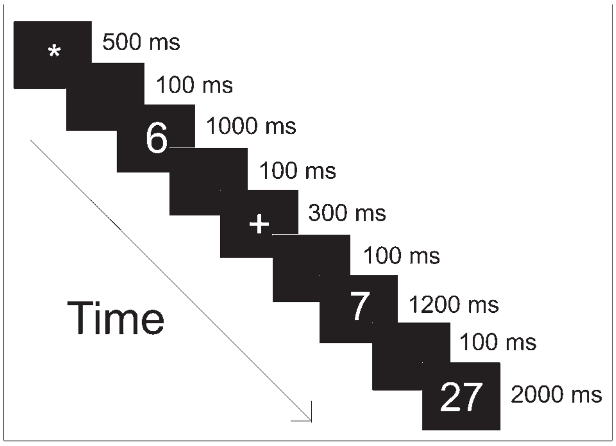

Fig. 1. The structure and timing of one trial.

3. Results

3.1. Behavioral data

Response times medians (RT) for correctly solved trials and the percentage of error responses were analyzed through analyses of variances (ANOVAs), taking the *proposed solution* (correct, small-split, large-split) as the within-subject factor and *group* (HMA, LMA) as the between-subjects factor.

Regarding response times, we found a significant main effect of *proposed solution* ($F(2,48) = 26.69$, $p < .001$, $\eta^2 = .52$), so that the small-split solution significantly differed from the correct ($p < .001$) and large-split ($p < .001$) solutions. As expected, the small-split solutions took more time (mean = 529.9, SEM = 27.6), than the correct (mean = 459.4, SEM = 23.4) and large-split (mean = 467.1, SEM = 18.4) solutions. Nevertheless, neither the main effect of *group* ($F(1,24) = .05$, $p = .81$, $\eta^2 = .002$) nor the *group* × *proposed solution* interaction ($F(2,48) = .17$, $p = .84$, $\eta^2 = .007$) reached statistical significance.

With respect to the percentage of errors, the main effect of *proposed solution* was also significant ($F(2,48) = 15.26$, $p < .001$, $\eta^2 = .38$), showing that the large-split solution significantly differed from the small-split ($p = .001$) and the correct ($p < .001$) ones. More concretely, the large-split solutions were the one with lower percentage of errors (mean = 1.92, SEM = .33) as compared to small-split (mean = 6.35, SEM = .92) and correct (mean = 6.25, SEM = .88) solutions. Similarly, no *Group* main effect ($F(1,24) = .15$, $p = .70$, $\eta^2 = .006$) or interaction ($F(2,48) = .02$, $p = .98$, $\eta^2 = .001$) was significant.

In order to reproduce the results obtained by Faust et al. (1996), flawed scores were computed by adding proportion of trials with

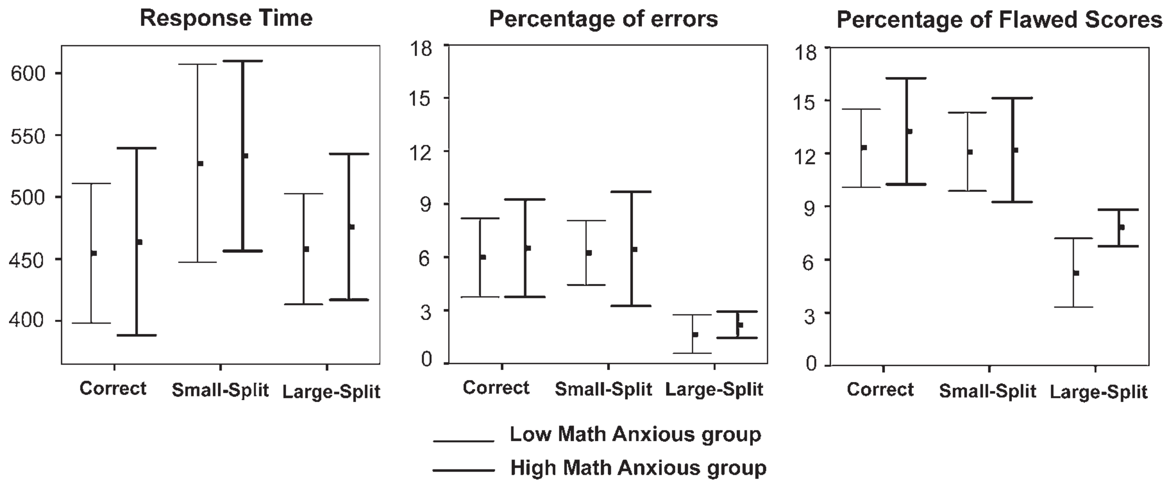

Fig. 2. Mean and standard errors (in bars) for response times (in ms), percentage of errors and flawed scores for correct, small-split and large-split problems in the two math anxiety groups.

erroneous answers to proportion of trials with extreme response times (outliers). Outliers were identified for each individual in each condition according to Tukey's method (Tukey, 1977). Given that one of our specific predictions was that there would be group differences in the large-split condition, we applied a Student's *t* test for independent samples to each proposed solution. Means differed between groups in the large-split condition ($t(24) = 2.26$, $p = .03$) but not in either the correct condition ($t(26) = .88$, $p = .38$) or the small-split condition ($t(24) = .05$, $p = .95$). Fig. 2 shows the higher percentage of flawed scores for the HMA group in the large-split condition and the lack of differences between groups in response times and percentage of errors.

3.2. *Event-related potentials*

ERPs in response to the proposed solution were averaged for each subject and for each condition. Hence, three averages were calculated per participant: one for correct solutions, one for small-split solutions and another for large-split solutions. The averages were calculated from correctly answered trials and were constructed from ±100 to 1000 ms epochs relative to stimulus onset. After trial rejection and EOG correction, the mean of epochs accepted for averaging was 133.3 in correct solutions, 134.3 in small-split solutions and 141.3 in large-split solutions. The minimum number of epochs included in any individual average was 111.

3.2.1. *P600/P3b amplitude*

Raw grand average ERPs produced in response to correct, small-split and large-split solutions at Pz are shown in Fig. 3. It can be seen that the large-split solutions elicited a positive wave peaking at about 200 ms post-stimulus for both groups, followed by a negative wave peaking between 200 and 300 ms and then by a P600/P3b component.

Given that the P600/P3b has different latencies in the correct and the split-solutions, we analyzed the ERP mean amplitude on different time windows, as other authors have previously done (Ford et al., 2001; Li, Gratton, Fabiani, & Knight, 2013; Teixeira Pinheiro, 2012). Thus, the small- and large-split solutions were analyzed at the 400–800 ms window, while the correct solution, for being earlier and more sharp, was analyzed at the 250–500 ms window. A repeated measures ANOVA was performed on the ERP mean amplitude at six electrodes (P3, Pz, P4, O1, Oz and O2), taking *proposed solution* (correct, small-split and large-split), *frontality* (parietal and occipital) and *laterality* (three levels from left to right) as within-subject factors and *group* (HMA and LMA) as the between-subjects factor. The Greenhouse–Geisser correction (Geisser & Greenhouse, 1958) for sphericity departures was applied when appropriate. The *F* value, the uncorrected degrees of freedom, the probability level following correction, the ε value (when appropriate) and the η^2 effect size index are given. Statistically significant interactions were identified by tests of simple effects, with the Bonferroni correction being applied in order to control for the increase in type I error.

The overall ANOVA revealed a significant main effect of *proposed solution* ($F(2,48) = 9.01$, $p = .003$, $\eta^2 = .27$, $\varepsilon = .65$), showing that the small-split solution differs from the correct ($p = .002$) and the large-split ($p = .05$) ones. More concretely, the small-split solution showed a less positive component (mean = 7.03, SEM = .59) as compared to the other two solutions (correct: mean = 9.55, SEM = .71; large-split: mean = 7.88, SEM = .63). Moreover, a significant main effect of *frontality* emerged ($F(1,24) = 45.15$, $p < .001$, $\eta^2 = .65$), being the amplitudes more positive at parietal (mean = 9.09, SEM = .59) than at occipital (mean = 7.21, SEM = .53) sites. More interestingly, the ANOVA showed a significant *group x proposed solution* × *frontality* interaction ($F(2, 48) = 4.04$, $p = .04$, $\eta^2 = .14$, $\varepsilon = .60$). Simple effect analyses were performed to compare amplitude in the HMA and LMA groups for correct, small-split and large-split solutions at parietal and occipital sites. Groups did not differ when they were presented with correct and small-split solutions, but they showed marginally significant differences at parietal

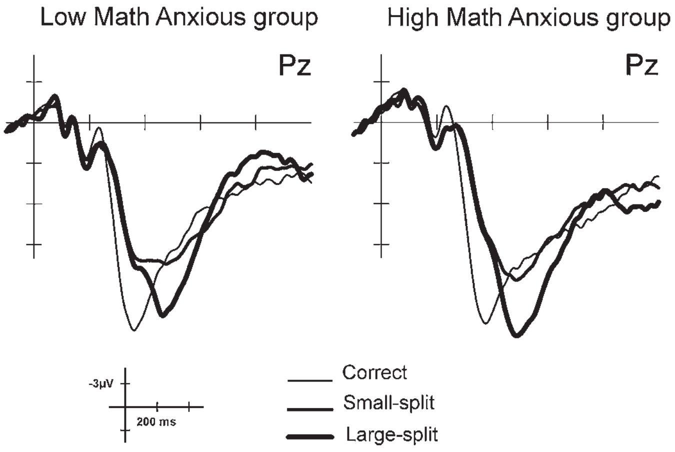

Fig. 3. Average waveforms elicited by correct, small-split and large-split solutions for the low and high math-anxious groups at Pz.

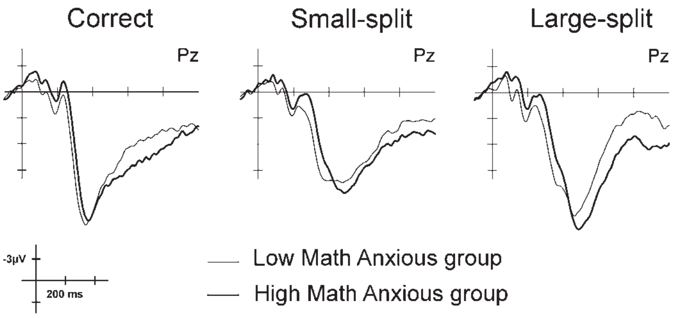

Fig. 4. Average waveforms elicited by LMA and HMA groups for the correct, small-split and large-split solutions at Pz.

($F(1,24)=3.36$, $p=.07$, $\eta^2=.12$) and occipital sites ($F(1,24)=3.14$, $p=.08$, $\eta^2=.11$) when they were presented with a large-split solution, revealing a larger amplitude P600/P3b component in the HMA group (parietal: mean = 10.28, SEM = .95; occipital: mean = 7.83, SEM = .89) than in the LMA group (parietal: mean = 7.80, SEM = .95; occipital: mean = 5.59, SEM = .89). Fig. 4 shows that the P600/P3b component has larger amplitude for the HMA group than for the LMA one in large-split solutions. Table 1 shows amplitude differences between groups in each condition. This amplitude difference is more evident in Fig. 5A, where topographic maps for correct (250–500 ms), small-split (400–800 ms) and large-split (400–800 ms) solutions are shown for both groups. The figure shows that while the P600/P3b component for the large-split condition has a centro-parietal distribution in both groups, its amplitude is larger for the HMA group. Finally, Fig. 5B shows difference in activation between conditions at the 400–800 ms window. For example, for the difference between large-split and small-split solutions, the HMA group seems to show a greater activation in broader locations than the LMA group. Topographic maps were plotted using the EEProbe 3.1 program (ANT Software BV, Enschede, The Netherlands).

3.2.2. *P600/P3b latency*

Fig. 4 also shows the latency difference between groups for each proposed solution at Pz. A repeated measures ANOVA was performed on the ERP mean latency in the 250–500 ms window for the correct solutions and in the 400–800 ms window for the small- and large-split solutions at six electrodes (C3, Cz, C4, P3, Pz and P4), taking *frontality* (central and parietal) and *laterality* (three levels from left to right) as within-subject factors and *group* (HMA and LMA) as the between-subjects factor.

The ANOVA showed a significant main effect of *proposed solution* ($F(2,48)=63.30$, $p<.001$, $\eta^2=.72$, $\varepsilon=.65$) so that correct solution differed from the small-split ($p<.001$) and the large-split ($p<.001$) solutions. More concretely, the P600/P3b appeared earlier in correct solutions (mean = 378 ms, SEM = 4.82) than in small-split (mean = 521.04 ms, SEM = 16.68) and in large-split (mean = 498.96 ms, SEM = 8.30) solutions. Small- and large-split solutions did not differ in latency ($p=.31$). More interestingly, we found a marginally significant *proposed solution* × *frontality* × *group* interaction ($F(2,48)=3.25$, $p=.06$, $\eta^2=.12$, $\varepsilon=.78$) showing that groups differed only when large-split solutions were presented at central ($F(1,24)=3.22$, $p=.08$, $\eta^2=.11$) and parietal ($F(1,24)=4.78$, $p=.03$, $\eta^2=.16$) sites, the HMA group being slower (e.g., at parietal sites: mean = 509.61 ms, SEM = 10.26) than the LMA one

Table 1
Means (standard error in brackets) for each group and means difference between groups (typical error in brackets) for amplitude (at parietal and occipital sites) and latency (at central and parietal sites) for the correct, small-split and large-split conditions.

Amplitude differences

	P3	Pz	P4	O1	Oz	O2
Correct solutions						
HMA	10.33 (4.75)	11.11(3.41)	10.58 (3.52)	8.46 (2.98)	8.33 (2.97)	8.22 (3.01)
LMA	10.20 (3.52)	10.21 (4.54)	9.94 (4.35)	9.47 (4.17)	8.88 (3.98)	8.85 (4.14)
Difference	.12 (1.64)	−.90 (1.57)	−.64 (1.55)	1.01(1.42)	.55 (1.38)	.62 (1.42)
Small-split solutions						
HMA	8.31 (3.01)	8.67 (3.01)	8.26 (3.25)	6.90 (2.64)	6.77 (2.85)	6.62 (3.07)
LMA	6.79 (3.31)	7.72 (3.65)	7.24 (3.79)	5.28 (2.84)	5.78 (2.93)	5.59 (3.26)
Difference	1.51 (1.24)	.95 (1.31)	1.02 (1.38)	1.62 (1.07)	.98 (1.13)	.67 (1.24)
Large-split solutions						
HMA	10.00 (3.63)	10.69 (3.63)	10.14 (3.70)	7.82 (3.06)	7.88 (3.33)	7.79 (3.47)
LMA	7.36 (3.00)	8.30 (3.33)	7.75 (3.61)	5.17 (3.06)	5.73 (3.24)	5.89 (3.33)
Difference	2.64 (1.30)*	2.38 (1.36)	2.39 (1.43)	2.65 (1.20)*	2.15 (1.29)	1.90 (1.33)

Latency differences

	C3	Cz	C4	P3	Pz	P4
Correct solutions						
HMA	373.07 (21.50)	368.53 (20.69)	380.61 (33.42)	388.84 (18.53)	384.46 (32.38)	379.92 (14.97)
LMA	380.53 (42.30)	371.53 (41.16)	372.00 (31.94)	381.84 (29.82)	381.84 (44.73)	375.92 (31.05)
Difference	−7.46 (13.16)	−3.00 (12.77)	8.61 (12.82)	7.00 (9.74)	2.61 (15.31)	4.00 (9.56)
Small-split solutions						
HMA	545.23 (127.91)	514.38 (104.37)	524.23 (112.56)	538.84 (98.95)	540.23 (112.02)	520.69 (97.37)
LMA	546.07 (113.34)	554.30 (93.75)	505.92 (99.17)	487.30 (78.21)	492.30 (69.17)	483.00 (58.37)
Difference	−.846 (47.40)	−39.92 (38.91)	18.30 (41.60)	51.53 (34.98)	47.92 (36.51)	37.69 (31.48)
Large-split solutions						
HMA	545.07 (94.07)	520.00 (61.29)	507.76 (58.82)	516.38 (52.03)	515.30 (54.04)	497.15 (39.55)
LMA	479.84 (40.75)	475.61 (33.87)	496.92 (89.71)	467.38 (32.38)	496.76 (67.71)	469.38 (34.63)
Difference	65.23 (28.43)*	44.38 (19.42)*	10.84 (29.75)	49.00 (16.99)**	18.53 (24.02)	27.76 (14.58)

Note. HMA: high math-anxious group; LMA: low math-anxious group; amplitude in µV; latency in miliseconds; difference: HMA–LMA.

* $p<.05$.

** $p<.01$.

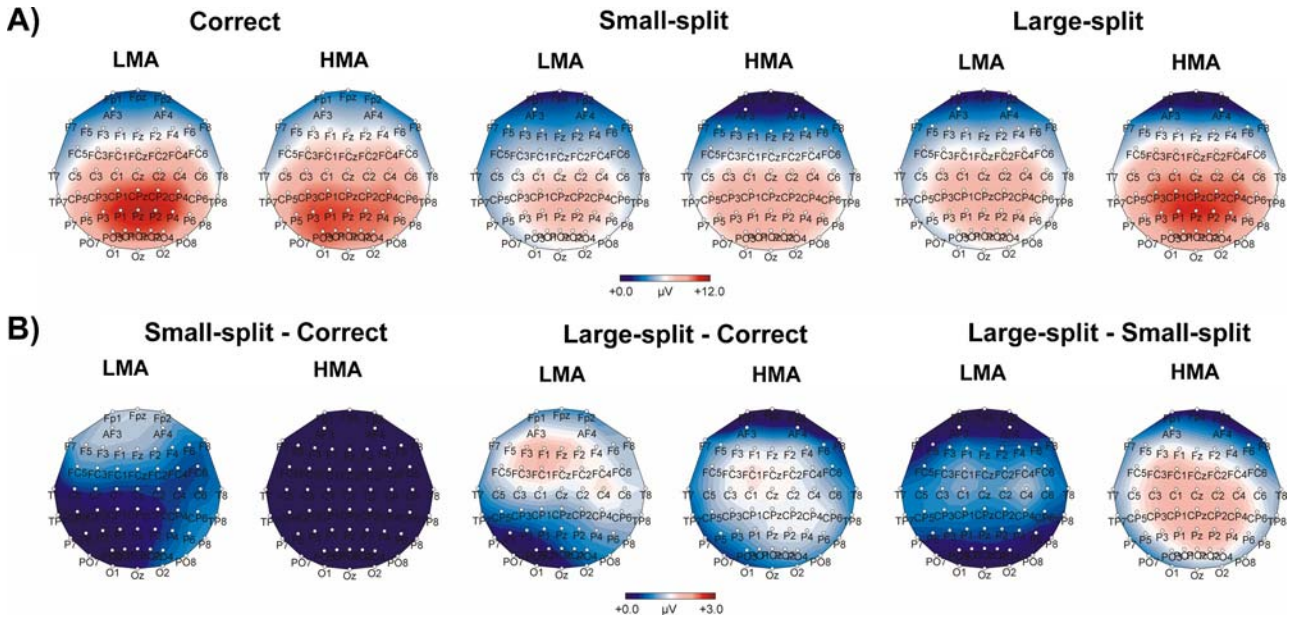

Fig. 5. (A) Scalp topography for the correct, small-split and large-split conditions for the low-math anxious (LMA) and high math-anxious (HMA) groups in the 250–500 ms (for correct solutions) and in the 400–800 ms (for small- and large-split solutions). (B) Scalp topography for the differences between conditions for the LMA and HMA groups in the 400–800 ms window.

(mean = 477.84 ms, SEM = 10.26). Table 1 shows latency differences between groups in each condition.

4. Correlational analysis

In order to analyze possible relationships between behavioral, ERP measures and math anxiety scores, the participants' scores in the sMARS test were correlated with the mean latency of the P600/P3b component in the 250–500 ms (for correct solutions) and in the 400–800 ms window (for small- and large-split solutions) at C1, Cz, C2, P1, Pz and P2 and the mean amplitudes for the component at the same time windows at P1, Pz, P2, O1, Oz and O2, for the whole sample ($n = 26$). The correlational analysis showed that the sMARS scores positively correlated with the P600/P3b latency at P1 ($r = .505$, $p = .009$) and P2 ($r = .448$, $p = .02$) only for the large-split condition. This correlation shows that as the levels of math anxiety increases, the P600/P3b component generated by large-split solutions is more delayed. All the other correlations between the P600/P3b latencies and the sMARS scores were non-significant. No significant correlations were found between the sMARS scores and the P600/P3b amplitudes.

Moreover, we found a significant negative correlation between the P600/P3b amplitude and the reaction time for the correct solutions at P1 ($r = -.530$, $p = .005$), Pz ($r = -.493$, $p = .01$), P2 ($r = -.462$, $p = .01$) and O2 ($r = -.390$, $p = .04$) and for small-split solutions at P1 ($r = -.441$, $p = .02$), Pz ($r = -.418$, $p = .03$) and P2 ($r = -.390$, $p = .04$). No such correlation was shown for the large-split solution. This correlation shows that as the P600/P3b amplitude became greater, the participant responded faster (lower reaction times). No correlation between behavioral measures and P600/P3b latency reached significance.

5. Discussion

The aim of the present study was to investigate, using the ERP technique, what happens in high math-anxious brains when a dramatically incorrect solution is proposed for a simple arithmetic problem. We looked for a possible electrophysiological correlate of the unexpected finding reported by Faust et al. (1996), in order to increase our understanding of the difficulties that high math-anxious individuals experience with mathematics. To this end, we formed two groups that were extreme in mathematical anxiety, but which did not differ in either trait anxiety or mathematical ability. This feature adds value to the study by enabling us to rule out the possibility that any differences between the two groups were due to these variables.

The ERPs and behavioral data confirmed our hypotheses. Firstly, we found a significant difference between the groups in flawed scores in the large-split condition,[3] with the HMA group producing higher flawed score rates than the LMA group, confirming that this group shows some difficulty in processing dramatically incorrect solutions. Secondly, there were no differences between the groups in response times or error rates. This result was expected given that the experimental task consisted in solving simple additions, the same task we used to equate mathematical ability when forming the groups and because, according to the ACT, anxiety affects processing efficiency to a greater extent than performance effectiveness. Finally, regarding ERP measures, large-split solutions elicited a parietal P600/P3b component that was present in both groups, but which had greater amplitude and longer latency in the HMA group.

As we explained above, the P3b amplitude is considered an index of the cognitive demands during task processing, with moderate increases in task demands (and, thus, devotion of more processing resources) being shown in increased P3b amplitude (Salisbury et al.,

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[3] We reproduced the findings of Faust et al. (1996) on the differences between groups in the large-split condition, but we did not find a similar level of flawed scores for the large-split and the split-1 condition. In fact, the percentage of flawed scores on the large-split condition is very similar in the two studies, but while Faust et al. (1996) found 8% of flawed scores for the small-split condition, we found 12% (which seems to show that our participants had greater difficulty in processing small-split solutions). This may be due to differences in the material used in each study. While Faust et al. (1996) put forward addends between 0 and 9, our study had addends between 2 and 9, since the evidence suggested that additions including "1" and "0" as addends are solved via rules rather than retrieval. Tie problems (4 + 4) were also excluded from our study. This makes our task slightly more difficult for participants than the one in Faust et al. (1996), which may explain the greater difficulty in processing small-split solutions that HMA individuals seem to have in our study.

2001). On the other hand, P3b latency is considered an index of the time needed to evaluate the stimulus. Accordingly, HMA individuals seem to be investing more processing resources and spending longer in evaluating large-split solutions than their LMA counterparts. As a consequence, our study seems to support the basic claim of the ACT, given that math anxiety appears to affect processing efficiency more than performance effectiveness. In other words, math anxiety has been shown to affect the speed of processing and the resources spent in solving simple additions when a large-split solution is proposed (the efficiency with which the task is performed) but not the quality of performance on the task (no differences were found between groups in reaction time and error rates). Nevertheless, flawed scores, a behavioral measure specifically designed to detect difficulties in processing, were able to show differences in performance effectiveness in math anxiety.

But why did the differences between groups (both in flawed scores and in ERPs) emerge only for the large-split condition? This result is counter-intuitive, given that high math-anxious individuals, being as skilled in mathematics as their LMA counterparts, would not be expected to differ on a simple arithmetic addition task, especially in a condition where the most implausible proposed solution is presented. According to the ACT, HMA individuals' attentional control deficit and their imbalance of goal-directed and stimulus-driven attentional systems make them especially vulnerable to distraction, because they find it difficult to resist (inhibit) disruption from salient or conspicuous stimuli. A distractor can be any novel stimulus, any abrupt onset of events or any stimulus largely differing from the context (Berti & Schröger, 2003). As a consequence, in our study, a large-split solution, clearly differing from the single-digit addends and dramatically distant from the correct solution, can be considered a distractor. According to this explanation, as the attentional system of HMA individuals is more influenced by the stimulus-driven attentional system, they would have succumbed to a salient stimulus such as the large-split solution, and would have devoted more time and more resources in processing a solution, which, in fact, could have simply been ruled out as implausible. In fact, the correlational analysis showed that the higher the level of math anxiety, the more time spent evaluating the large-split solution. Moreover, the large-split solution was the only one in which a higher amplitude of the P3b component did not correlate with a decrease in response time, suggesting that while in the other conditions the involvement of more processing resources was related to faster responses, this did not happen in the large split condition.

Furthermore, the ACT claims that the negative effects of anxiety on performance are greater when overall processing demands are high, because anxious individuals have insufficient processing capacity to regain attentional control. Nevertheless, other studies based on Lavie' load theory suggest the opposite: that anxiety-related deficits in recruitment of attentional control are seen when external demands are low (Bishop, 2009). More specifically, Lavie's theory of attention and control (Lavie, Hirst, Fockert, & Viding, 2004) states that the need for active recruitment of attentional control mechanisms depends on the processing requirements (or perceptual load) of the task in hand: when processing requirements are high, the task is considered to fully occupy attentional resources, and thus to leave no resources to process distractors. As a consequence, distractors cannot compete for further processing and their processing simply finishes at an early stage. Nevertheless, when the processing requirements of the primary task are low, resources are available for processing distractors, and they may therefore receive further processing, such as response selection or working memory; at this point attentional control is needed in order to maintain processing priorities, inhibiting distractor-related processing and supporting task-related processing.

Despite this difference, both the ACT and the anxiety-related studies based on Lavie's theory claim that attentional control is needed to inhibit distractor-related processing in order to avoid the possible effects of extended processing at later stages such as response selection. Along these lines, previous studies have shown that groups characterized by weakened attentional control, such as older individuals as compared to younger ones (Maylor & Lavie, 1998) or children as compared to adults (Huang-Pollock, Carr, & Nigg, 2002) showed increased disruption by distractors under tasks/conditions with low processing requirements. More interestingly, a study using fMRI found that high trait-anxious individuals showed a deficient recruitment of the dorsolateral prefrontal cortex (an area involved in the increase in attentional control in response to processing conflict) to inhibit distractor processing under conditions in which the allocation of attentional resources was not fully governed by the primary task (Bishop, 2009).

Our study seems to corroborate Lavie's theory, given that we found math anxiety effects on a task in which processing requirements are very low (solving single-digit additions). According to this theory, the effects of the distractor (large-split solutions) would have been considerably reduced if the task requirements had been higher, as in the case of solving a more complex arithmetical operation (e.g., an addition task involving double-digit numbers with carrying and borrowing).

Exploring the unexpected finding of difficulties in processing large-split solutions in HMA individuals with the help of a sensitive technique (ERPs), we found latency and amplitude differences between groups in the processing of large-split solutions. Using standard behavioral measures, Ashcraft and Faust (1994) and Faust et al. (1996) did not find differences between groups in simple arithmetic; this led them to put forward the *anxiety–complexity effect*, which suggests that there are no (or only quite subtle) anxiety-related differences in performance in the simple arithmetical operations of addition, and that math anxiety only affects complex mathematics. On the other hand, other studies, also using behavioral measures, found that high math-anxious individuals showed a basic numerical processing deficit in a visual enumeration task (Maloney, Risko, Ansari, & Fugelsang, 2010) and in a symbolic numerical comparison task (Maloney, Ansari, & Fugelsang, 2011). Regarding our study, we obtained no differences between groups for response time or error rates, a finding that supports the anxiety–complexity effect (no differences in simple math performance). Nevertheless, using ERPs we found that although anxiety seemed not to affect simple arithmetical performance, it did affect the way HMA individuals process the proposed solutions, implying that anxiety affects the processing efficiency of even very simple arithmetical problems.

To sum up, this study explored the electrophysiological correlate of the curious flawed scores pattern found by Faust et al. (1996). Using ERPs we found that large-split solutions generated an enhanced and delayed P600/P3b component for the HMA group. This result suggests that ERP effects were only found for large-split solutions because it is the only proposed solutions that deviate sufficiently far from the previous context, and thus, the only one constituting a distractor. Moreover, these effects were only found for the HMA group because, according to the ACT, they are characterized by an attentional control deficit that makes it difficult for them to inhibit the processing of distractors. As a consequence, in front of a large-split solution, HMA individuals spent more time and devoted more resources to the processing of a proposed solution which, though salient, could have been ruled out very easily. Therefore, our study proposes that the pattern of flawed scores found by Faust et al. (1996), interpreted as HMA individuals' difficulties in processing large-split solutions, has to do with their difficulty in inhibiting the processing of irrelevant information, which increases the time and resources needed for processing it, and explains why

HMA individuals differ from their LMA counterparts in terms of processing efficiency when responding to implausible solutions in a simple addition task.

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Study III

Reactive Recruitment of Attentional Control in Math Anxiety: An ERP Study of Numeric Conflict Monitoring and Adaptation

Macarena Suárez-Pellicioni[1,2], **María Isabel Núñez-Peña**[1,2]*, **Àngels Colomé**[1,3]

1 Department of Behavioral Sciences Methodology, Faculty of Psychology, University of Barcelona, Barcelona, Spain, **2** Institute for Research on the Brain, Cognition and Behavior (IR3C), University of Barcelona, Barcelona, Spain, **3** Department of Basic Psychology, Faculty of Psychology, University of Barcelona, Barcelona, Spain

Abstract

This study uses event-related brain potentials (ERPs) to investigate the electrophysiological correlates of numeric conflict monitoring in math-anxious individuals, by analyzing whether math anxiety is related to abnormal processing in early conflict detection (as shown by the N450 component) and/or in a later, response-related stage of processing (as shown by the conflict sustained potential; Conflict-SP). Conflict adaptation effects were also studied by analyzing the effect of the previous trial's congruence in current interference. To this end, 17 low math-anxious (LMA) and 17 high math-anxious (HMA) individuals were presented with a numerical Stroop task. Groups were extreme in math anxiety but did not differ in trait or state anxiety or in simple math ability. The interference effect of the current trial (incongruent-congruent) and the interference effect preceded by congruence and by incongruity were analyzed both for behavioral measures and for ERPs. A greater interference effect was found for response times in the HMA group than in the LMA one. Regarding ERPs, the LMA group showed a greater N450 component for the interference effect preceded by congruence than when preceded by incongruity, while the HMA group showed greater Conflict-SP amplitude for the interference effect preceded by congruence than when preceded by incongruity. Our study showed that the electrophysiological correlates of numeric interference in HMA individuals comprise the absence of a conflict adaptation effect in the first stage of conflict processing (N450) and an abnormal subsequent up-regulation of cognitive control in order to overcome the conflict (Conflict-SP). More concretely, our study shows that math anxiety is related to a reactive and compensatory recruitment of control resources that is implemented only when previously exposed to a stimuli presenting conflicting information.

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* E-mail: inunez@ub.edu

Introduction

The anxiety towards mathematics has been defined as a "feeling of tension and apprehension surrounding the manipulation of numbers and the solving of mathematical problems in academic, private and social settings" [1]. This type of anxiety has been attracting considerable research interest in recent years given that its negative impact on students' mathematical development is becoming increasingly clear. In this respect, math anxiety is one of the main causes of math avoidance, the tendency of these students to avoid courses and career paths that are related to numbers, a response that stops their mathematical learning at an earlier stage as compared to their low math-anxious counterparts [2]. Undoubtedly this fact has its negative consequences on their professional development, employment opportunities, and even salary prospects.

Beyond these educational and social effects of math anxiety, several investigations have shown that a high math-anxious brain does not work like a low math-anxious one. For example, it has been demonstrated that high math-anxious individuals show: less precise representations of numerical magnitudes [3]; difficulties in counting objects in a visual enumeration task [4]; difficulties in solving complex arithmetic problems [5]; difficulties in processing large-split solutions in simple arithmetic verification [6]; greater cognitive effort and resource investment in preparation for a task goal [7]; abnormal error monitoring for errors committed in a numerical task [8], etc.

The Attentional Control Theory [9] (henceforth ACT), based on the processing efficiency theory [10] (henceforth PET), is one of the main theories trying to explain the negative effects of anxiety on cognitive performance. The original distinction between performance effectiveness (quality of task performance) and processing efficiency (relationship between effectiveness and the amount of resources or effort spent on solving the task), as well as the claim that anxiety affects the latter to a greater extent than the former, are central to ACT. This theory uses the working memory model proposed by Baddeley [11], comprising a central executive (i.e., a modality-free system that controls incoming information) and two slave systems. In this theory, the functions of the central executive are impaired by anxiety, with the inhibition function being one of the most affected [12]. More concretely, according to this theory, anxiety alters the balance between the stimulus-driven attentional system and the top-down goal-driven attentional system [13], reducing the influence of the latter. As a result, high anxious individuals are more easily distracted as compared to low anxious ones. Nevertheless, anxious individuals are considered to compensate for this reduction in efficiency by means of a reactive recruitment of additional attentional resources if these are available.

In this line, Braver and colleagues' dual mechanisms of control (DMC) theory [14] accounts for two ways of exerting cognitive control that would be associated with the level of anxiety. On the one hand, low anxious individuals are considered to engage top-down control in a *proactive* way, which implies a sustained representation of task requirements or goals. This type of control would allow for more effective top-down control of processing and would promote preparatory attentional and response biases and the prevention of conflict during ongoing processing. By contrast, high anxious individuals are considered to exert control in a *reactive* way, consisting of an only-when-needed late correction character. This type of control implies that, after task goals are first coded, they are not maintained in a continuously active state. In other words, task representations are reactivated only when a task-relevant stimulus is encountered or conflict occurs in processing. This entails weaker preparatory attentional biases, and processing is therefore more easily influenced by bottom-up input. As a consequence, high anxious individuals would be more easily distracted than their low anxious counterparts.

Cognitive control effects have traditionally been measured using the Stroop task. In the original Stroop color-naming task, introduced more than 75 years ago [15], color words are presented in varying colors, and the participant is asked to name the color of the ink (target dimension) while ignoring the word meaning (distractor dimension). An incongruent target-distractor pairing (e.g., the word RED written in blue ink) induces a stimulus-response conflict as compared with congruent target-distractor pairings (e.g., the word RED written in red ink). The *Stroop interference effect* consists of an increase in response times in incongruent trials compared with congruent ones, and has been suggested to show the difficulty in inhibiting attention to meaningful but conflicting information, even when that information is not relevant for solving the task [16].

Following the pioneering research of Stroop (1935), the Stroop interference effect has also been observed using numbers. There are two main numerical Stroop paradigms: one (also called counting task) in which the numerical magnitude denoted by the Arabic digits interferes with saying how many of them there are (e.g., having to say "four" to 3333) [17,18], and another in which the physical size of the digit interferes with its numerical magnitude or vice versa (e.g., 2 8) [19]. Similarly to their performance on the classic Stroop task, individuals performing the numerical Stroop task take longer and commit more errors when responding to incongruent (e.g., 3333 or 2 8) than to congruent (e.g., 333 or 2 8) trials (i.e., the *numerical interference effect*).

Given the ability of this task for measuring conflict and inhibitory processing, it seems very suitable for assessing the negative effects of anxiety. For example, using a classic Stroop task, Pallak et al. (1975) found that high anxious individuals showed slower response times in the condition presenting conflicting information, that is, in incongruent trials, as compared to the low anxious ones [20]. Similarly, using the same task, another researcher found that individuals in the high-stress condition performed significantly worse than the ones in the low-stress condition, but only for incongruent trials [21,22].

Despite the relative infancy of math anxiety research, the susceptibility of high math-anxious (HMA) individuals to distraction has already been tested [17,23]. Hopko et al. (1998) formed three groups of participants according to their level of math anxiety (low, medium, and high) and administered a task designed to measure their ability to inhibit attention to distracting phrases in a reading task. Reading conditions consisted of paragraphs that were categorized by content (i.e., math or non-math) and distractor type (i.e., control, related, and unrelated). Related distractors were math words that were unrelated to paragraph content, unrelated distractors were non-math words also unrelated to paragraph content and, finally, control distractors were a string of Xs, equivalent in length to the other types of distractors, and inserted in the same locations as distracters in the other two conditions. They found that HMA individuals took significantly longer to read paragraphs with distractors embedded in the text than did low math-anxious (LMA) participants. Nevertheless, this slowdown was also shown when paragraphs were unrelated to mathematics, which was taken as evidence supporting HMAs' difficulty in inhibiting attention to any kind of distractor. Some years later, Hopko et al. (2002) measured those difficulties in attention inhibition in math anxious individuals by using the counting version of the numerical Stroop task. To this end, they formed two groups according to participants' level of math anxiety (top and bottom 20% of the distribution). Participants were administered a card version of the numerical Stroop task containing both numerical (e.g., 9999) and non-numerical (e.g., HHHH) materials. Participants' task consisted in saying the quantity of elements (numbers or letters) on each card. In the case of the numerical material, the stimuli were always incongruent. They found that the HMA group showed longer response times with both the numerical and the non-numerical materials, as compared to the LMA group. Nevertheless, this slowdown was significantly higher for the task including numerical material than for the one including letters. The authors interpreted their results in line with previous research [23,24], suggesting that HMA individuals may possess a more trait-like inability to suppress attention to distracting information, a deficit that seemed not to depend on, but to be somehow enhanced by exposure to numerical stimuli.

Although interference effects in math anxiety have previously been shown in behavioral measures, they have never been studied using more sensitive techniques. For this reason, the main objective of this study was to investigate interference effects in math anxious individuals by means of the event-related potentials (ERPs) technique, which provides a measure of brain dynamics with high temporal resolution, allowing a characterization of the cascade of processes that behavioral measures cannot offer. In this respect, conflict-related effects have been found at very early stages of processing, like the P1 component. The P1 component is a positive-direction component appearing at the parieto-occipital electrodes between 100 and 150 ms post-stimulus which is thought to reflect processing of the low-level features of stimuli [25]. Previous authors have hypothesized that it is generated in posterior occipito-temporal areas [26] and is influenced by amygdala in fear processing [27]. Using compound stimuli consisting of a facial expression with an expressive body, Meeren et al. (2005) found a larger P1 ERP component at posterior brain sites when the expression of the face and the emotion portrayed by the body conflicted than when they were congruent [28].

Despite conflict-related findings for the P1 component, the N450 component and the conflict sustained potential (henceforth Conflict-SP) [18,29–35], consistently identified in the incongruent minus congruent differences wave, are the main ERP components associated with conflict processing. The N450 component is a negative-going ERP deflection appearing from approximately 350 to 500 ms post-stimulus at fronto-central sites. Recent evidence has suggested that this component is related to stimulus conflict processing (i.e., at the level of stimulus representation) rather than to response conflict processing (i.e., at the level of motor response organization) [19]. Source analysis indicates that the neural generators of N450 may lie within the anterior cingulate cortex (ACC) [29,32], which supports the suggestion that this component reflects conflict detection [18,32,36]. Moreover, it shows greater negativity when the level of conflict increases (e.g., reducing the proportion of incongruent stimuli) [31], consistent with previous evidence pointing to an increase in ACC activity in high conflict situations [37].

The N450 is directly followed by a positive-going Conflict-SP, emerging at central sites roughly 500 ms after stimulus onset [35]. Its sources have been suggested to be located within the middle or inferior frontal gyrus (LPFC) and the left extrastriate cortices [31]. The cognitive processes underlying this component are more ambiguous in the literature than those of N450, but they have been associated with general preparation [33], conflict resolution [31,32], response selection [18], and the execution of top-down control [38]. Their amplitude also varies with the level of conflict, being more positive for high conflict conditions (i.e., when incongruent stimuli are presented in lower proportion) as compared to low conflict ones [39].

Beyond conflict monitoring, another way to study possible deficits in conflict processing is through studies of conflict adaptation (also referred to as sequential-trial effects, trial-to-trial effects, or Gratton effects) [40]. Gratton et al. (1992) observed that, apart from the expected main effect of congruence of the current trial (i.e., longer response time and error rates for incongruent as compared to congruent trials), there was an interaction between current and previous trial congruence, in which the interference was higher following congruent trials than following incongruent ones. The conflict monitoring model (CMM) holds that the conflict adaptation effect stems from conflict-driven adjustments in cognitive control [41]. When an incongruent trial is presented, a simultaneous activation of competing responses (response conflict) is produced. This conflict is detected by a conflict-monitoring mechanism, thought to reside in the anterior cingulate cortex (ACC), which triggers an up-regulation in cognitive control, thought to be implemented by the lateral prefrontal cortex (LPFC), in order to overcome the conflict. Activation in the ACC, reflected in N450, and subsequent activation in the LPFC and left extrastriate cortices, reflected in Conflict-SP, are consistent with the theory that the ACC and prefrontal regions are involved in evaluative processes and subsequent strategic adjustment in attentional control to reduce future conflict [39,42–44]. As a consequence, the level of cognitive control is high following an incongruent trial. In contrast, congruent trials are not associated with response conflict and do not result in a temporary up-regulation of cognitive control. Hence, the level of control is low following a congruent trial.

Regarding ERPs, the N450 component has been suggested not to be influenced by the congruence of the previous trial, that is, not to exhibit a significant conflict adaptation effect. Consequently, it has been considered to reflect a more automatic conflict monitoring mechanism that would not be influenced by the implementation of top-down control [38]. However, recent evidence in the field of anxiety has found variations in this component according to the congruence of the previous trial, and thus has suggested that this component reflects more than an automatic process [45]. On the other hand, Conflict-SP has also been shown to index previous-trial congruence, showing greater amplitude for the interference effect preceded by congruence (*cI-cC*) than for the interference effect preceded by incongruity (*iI-iC*). The greater amplitude of Conflict-SP when preceded by congruence implies a higher level of interference (the greater the amplitude, the greater the interference), given that attentional control is considered not to be enhanced by the preceding congruent trial. On the contrary, a reduction in its amplitude when preceded by incongruity trials has to do with a reduced level of interference, given that an enhanced attentional control is considered to have been exerted in the preceding incongruent trial. This evidence suggests that the amplitude modulations of this Conflict-SP reflect conflict adaptation effects, that is, controlled processes signaling for increased implementation of attentional control after conflict detection [38,39,46].

Previous evidence has shown that trait anxiety is closely related to individual differences in dynamic adjustments of attentional control, supporting the association between high anxiety and a reactive use of attentional control suggested by the DMC account [14] and the ACT [9]. As commented above, Osinsky et al. (2010), using a gender discrimination Stroop task (This task consists of the presentation of male and female faces together with the word "woman" or "man", which results in congruent trials (e.g., a woman's face with the word "woman") and incongruent trials (e.g., a man's face with the word "woman") and participants have to respond to the gender of the face, while the word acts as a distractor), found a more negative deflection in the N450 time window in the context of preceding incongruent trials as compared to preceding congruent trials for the high trait-anxious group, suggesting that these individuals more strongly engage neural mechanisms of conflict-monitoring only when previously exposed to a high level of stimulus-response conflict (i.e., only after incongruent trials) [14,47,48]. Some years later, the same research group performed a similar experiment using the same gender discrimination task (face-word pairings) but incorporating trials where only the relevant dimension of the task was presented (face-only trials) and others where only the task-irrelevant dimension of the task was shown (word-only trials) [45]. For the face-word and the face-only stimuli, participants were instructed to discriminate the sex of the presented faces, while they were instructed to react to the word meaning of the word-only stimuli. The N170 and N400, two ERPs components related to face and word processing, respectively, were analyzed. They found that high trait-anxious participants showed a higher N170 component for face-only trials when preceded by incongruent face-word pairings, signaling faster face discrimination after conflict processing, and higher N400 for the word-only condition, suggesting slower word discrimination, and thus suppressed processing of the task-irrelevant dimension of the task. They interpreted their results as evidence suggesting that high trait anxiety is linked to a reactive and compensatory recruitment of attentional control resources following a conflict between task-relevant and task-irrelevant stimuli, as previously suggested by other authors [14,47].

As we noted previously, although susceptibility to distraction in math anxious individuals has been studied previously by means of behavioral measures [17,23] no work to date has investigated its electrophysiological correlates. Studying numeric interference by means of the sensitive ERP technique would allow us to identify two main conflict-related ERP components, N450 and the subsequent Conflict-SP, and thus to further investigate whether math anxiety is related to an earlier conflict detection and/or to a later response-related stage of processing. Similarly, conflict adaptation effects in math anxiety have never been studied. Since neural and behavioral evidence of conflict adaptation is sensitive to subtle differences in cognitive processing, it can be especially useful for identifying the specific nature of cognitive processing deficits in math anxious individuals when they have to deal with conflicting information.

With these objectives in mind, we formed two groups that were extreme in their level of mathematical anxiety (top and bottom 25% of the distribution forming the HMA and LMA groups, respectively). Groups did not differ in trait or state anxiety or in math ability, in order to rule out the possibility that any group differences could be explained by differences in these variables. Participants performed a single-trial version of the numerical Stroop task presenting conflict between numerical magnitude and physical size, while their ongoing EEG was recorded. Two main effects were analyzed: conflict monitoring effects and conflict adaptation effects. While the former analysis assessed the congruence effect of the current trial, the latter studied modulations in attentional control for the current interference effect depending on the congruence of the previous trial. In the case of the first main effect, the conflict monitoring analysis was performed by comparing the N450 and Conflict-SP components between groups for the interference effect (incongruent-congruent difference wave). It has been suggested that it is very difficult to measure the amplitude and latency directly from a raw ERP waveform without distortion from overlapping components. For this reason, creating difference waves can constitute a good strategy for isolating the component of interest [49]. In the case of the second main effect, the conflict adaptation analysis was performed by comparing the same ERP components between groups for the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*). Our hypotheses were as follows. Regarding the conflict monitoring analysis, we expected: 1) to reproduce previous findings on math anxiety [17,23], by obtaining a higher interference effect (incongruent-congruent) in response times for the HMA group as compared to the LMA one. Differences were expected for response times and not for error rates given that, according to the ACT, behavioral consequences of anxiety-related deficits would affect response time (i.e., processing efficiency) but not accuracy (i.e., performance effectiveness) [9]. 2) Regarding ERPs, as suggested by previous evidence, conflict-related brain potentials should increase with the level of anxiety [45], so we expected greater N450 and/or Conflict-SP amplitudes for the HMA group as compared to the LMA group. As for the conflict adaptation analysis, we expected: 3) to find the conflict adaptation effect for the two groups, with the interference effect expected to be smaller when preceded by incongruity than when preceded by congruence [44] given that incongruity in the previous trial would have enhanced attentional control and thus would have reduced the influence of the distractor. No differences between groups were expected for this conflict adaptation effect in behavioral measures, as suggested by previous evidence analyzing this effect in trait anxiety [48]. 4) Differences between groups were expected to be found in ERPs though. Given that there is no clear evidence for conflict adaptation modulations for the N450 component, with some authors suggesting that it reflects a more automatic conflict monitoring mechanism, not influenced by variations in attentional control [38] and another study reporting a modulation of the N450 component by previous trial congruence in trait anxiety [48], no clear hypothesis were formulated for this component. On the contrary, conflict adaptation effects were expected for the Conflict-SP, a component clearly linked to the execution of top-down control [18,29,32,38]. Thus, if, as suggested by the ACT [9] and the DMC [14], anxiety is related to a reactive recruitment of attentional control [45,48], then the HMA group would exert attentional control only after incongruent trials (i.e. when conflict is encountered in processing), so they should show a reduced Conflict-SP for the interference effect preceded by incongruity (*iI-iC*) as compared to the interference effect preceded by congruence (*cI-cC*) (i.e. the greater the conflict, the greater the Conflict-SP). On the other hand, the LMA group, considered to engage top-down control in a proactive or sustained way, should show no difference in the Conflict-SP component for the interference effect depending on the congruence of the previous trial.

Methods

Participants

Thirty-four healthy volunteers were tested in this study, half of them with a high level of math anxiety (HMA) and the other half with a low level (LMA). They were selected from a sample of 490 university students from the University of Barcelona who were assessed for math anxiety, trait and state anxiety and simple math ability.

The LMA group comprised seventeen participants (age range = 19–26, mean = 21.18, SEM = .50), who scored below the first quartile in the Abbreviated Mathematics Anxiety Rating Scale (sMARS) [50] (score range = 35–52, mean = 45.76, SEM = 1.22). The HMA group also comprised seventeen participants (age range = 19–25, mean = 20.82, SEM = .41), but these scored above the third quartile in the sMARS (score range = 76–102, mean = 85.29, SEM = 1.61). More detailed information about the two groups is shown in Table 1.

Groups differed in math anxiety ($t(32) = 19.49$, $p < .001$), but not in trait anxiety ($t(32) = .66$, $p = .51$), state anxiety ($t(32) = 1.67$, $p = .11$), simple math ability ($t(31) = .54$, $p = .59$), age ($t(32) = .53$, $p = .59$), years of formal education ($t(32) = 1.19$, $p = .24$), handedness ($\chi^2 = .00$, $p = 1$), ethnicity ($\chi^2 = 1.03$, $p = .31$) or gender distribution ($\chi^2 = .18$, $p = .67$).

All participants had normal or corrected-to-normal visual acuity and did not report any history of neurological or psychiatric disorders. All were naïve as to the purposes of the study.

Ethics Statement

Participants were paid for their participation and gave written informed consent before the experiment. The experimental protocol was approved by the Bioethics Committee of the University of Barcelona and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Materials

During the screening phase of the study. The following tests were administered in order to form groups. They were presented to the participant in the following order:

Simple Arithmetic Test: This test consists of 165 single-digit addition problems of the form "a+b = " organized into five columns. There were 24 different additions involving operands between 2 and 9. No addition included the numbers 1 or 0 or tie problems (i.e. 4+4). Individuals were instructed to solve the additions as fast and as accurately as possible within a time limit of two minutes. This test has been previously used for measuring simple arithmetic ability in another study performed by our lab [6]. Given the simplicity of the task (the most difficult addition was 8+9 =), the accuracy in solving it (the proportion of correctly solved additions with respect to the total of additions solved) was taken as a measure of participants' simple arithmetic ability.

Abbreviated Mathematics Anxiety Rating Scale (sMARS) [50]: The sMARS is a 25-item version of the Math Anxiety Rating Scale (MARS) [1]. This instrument measures anxiety by presenting 25 situations which may cause math anxiety (e.g., *Being given a homework assignment of many difficult problems that are due in the next class*

Table 1. Means and standard errors of the mean (SEM; in brackets) for age, educational level, math ability, math anxiety, trait and state anxiety and frequencies for gender and handedness for the LMA and the HMA groups.

	Age	Gender	Handedness	Education	Ability	sMARS	STAI-T	STAI-S
LMA	21.18 (.50)	13	16	15.65 (.44)	.98 (.004)	45.76 (1.22)	20.06 (2.56)	14.24 (8.21)
HMA	20.82 (.41)	14	16	15.00 (.30)	.98 (.006)	85.29 (1.61)	22.53 (2.68)	19.18 (8.97)

Note: LMA: low math-anxious; HMA: high math-anxious; Gender: number of women; Handedness: number of right-handed individuals; Education: number of years of formal education counting from 6 years-old forward. Ability: proportion of correctly solved additions with respect to the total of additions solved in the Simple arithmetic test. sMARS: shortened Math Anxiety Rating Scale; STAI-T: Trait anxiety subscale from the STAI; STAI-S: State anxiety subscale from the STAI.

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meeting). Participants decide on the level of anxiety associated with each item by answering on a five-point Likert scale from 1 (no anxiety) to 5 (high anxiety). The sum of the item scores provides the total score for the instrument, which ranges from 25 to 125. In the present study, the Spanish version of the sMARS [51] was used. The scores for the Spanish version of the sMARS have shown strong internal consistency (Cronbach's alpha = .94) and high 7-week test-retest reliability (intra-class correlation coefficient = .72).

State-Trait Anxiety Inventory (STAI) [52]: It includes 40 statements describing different emotions, 20 for measuring state anxiety (STAI-S) and 20 for trait anxiety (STAI-T). Items are answered on a four-point Likert scale. In the STAI-S the answer options go from 0 (not at all) to 3 (very much) and subjects have to answer by taking into account how they feel "right now". In the STAI-T the answer options go from 0 (rarely) to 3 (almost always) and subjects have to answer by taking into account how they feel "in general" [52]. Good to excellent internal consistency (Cronbach's alpha = .86–.95) and adequate test–retest reliability (State: $r = .71–.76$; Trait: $r = .75–.86$) has been reported [52]. The Spanish version of this test has been used in this study, which also has shown good psychometric properties [53].

During the recording session. Participants were administered a numerical Stroop task comprising pairs of Arabic numbers (1–2, 1–8, 2–9 and 8–9) shown simultaneously in the middle of the computer screen. Numbers were presented in two sizes: large (font 80) and small (font 40). Stimulus pairs appeared at subtended viewing angles of 0.68° and 1.37° (horizontally) and 0.97° and 1.77° (vertically) for large and small sizes, respectively. Participants were asked to respond to the number of higher numerical magnitude, ignoring physical size. The stimuli could be congruent (the number of larger numerical magnitude was also larger in physical size; e.g., 8 9) or incongruent (the number of larger numerical magnitude was smaller in physical size; e.g., 8 9) [54]. The task included congruent and incongruent stimuli in equal proportions and all the stimuli were presented an equal number of times and randomly to each participant.

Participants were instructed to indicate the number of larger numerical magnitude by clicking on the left or right button of the mouse, depending on the side of the screen in which it had appeared. The side on which the larger number appeared was counterbalanced, so there were two instances for all number pairs (e.g., 8 9 and 9 8). They were asked to respond as fast and as accurately as possible.

The E-prime 2.0 program (Psychology Software Tools Inc., Sharpsburg, PA, USA) was used to control the presentation and timing of the stimuli and to measure response accuracy and response time.

Procedure

Participants were tested individually. Upon entering the experimental room, they completed standard procedures concerning informed consent along with a demographic questionnaire asking their age, ethnicity, gender, and number of years of formal education. Then, EEG/EOG sensor electrodes were attached and the participant was given detailed task instructions. After that, participants were seated 100 cm away from a computer screen in an electrically-shielded, sound-attenuating recording chamber. The experimental session began with a training period of 24 trials. When participants achieved 65% of hits in the training period, the recording session started (if not, the training was repeated). The training trials were used only to familiarize the participants with the task, so they were excluded from the statistical analysis.

Each trial began with a fixation sign (an asterisk) shown for 500 ms. After a 300 ms pause (black screen), a pair of numbers were shown for 300 ms and then followed by a 700 ms-black screen (maximum response window of 1000 ms). Each trial was followed by a variable inter-trial interval ranging from 600 to 1100 ms (black screen). Participants responded to 160 total trials, 80 per condition, organized into 5 blocks of 32 stimuli and preceded by the 24 practice stimuli. The whole session lasted about 120 minutes. Figure 1 shows the sequential presentation of an incongruent stimulus and its timing.

Electrophysiological Recording

The EEG was recorded with ANT hardware and software (B.V., Enschede, The Netherlands) from 64 electrodes mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH. ANT Advanced Neuro Technology) and positioned according to the extended 10/20 system, as well as two electrodes on the right and left mastoids. EEG channels were continuously digitized at a rate of 512 Hz by an ANT amplifier (B.V., Enschede, The Netherlands). A band-pass filter was set from 1.6 to 30 Hz, and electrode impedance was kept below 5 kΩ. The horizontal and vertical electrooculogram was recorded with electrodes placed at the outer canthus and below the right eye, respectively. The common reference electrode was placed on the tip of the nose and the ground was located at AFz. For data analysis, they were re-referenced to the mean activity of all sites [55]. Ocular artifacts were identified and corrected with the eye-movement correction algorithm used in the EEprobe program (ANT, The Netherlands). For graphical presentations only, a 15-Hz low-pass filter was applied.

Data Analysis and Results

Behavioral Data

Conflict monitoring analysis. Medians of response times (RT) for correctly solved trials and percentage of hits were calculated for each participant in each condition (congruent and incongruent). Following previous studies, we calculated a single score index of interference by subtracting congruent from incongruent trial latencies for the RT analysis and incongruent from congruent hit rates in the accuracy one (i.e. for both indices, the greater the value, the greater the interference) [48]. A *t* test was carried out to look for group differences in the interference effect.

Regarding response times, significant differences were found between groups ($t(32) = 2.10$, $p = .04$), with the HMA group showing a greater interference effect (mean = 72.50 ms, SEM = 8.15) than the LMA one (mean = 52.02, SEM = 5.30).

No significant differences were found for percentage of hits ($t(32) = .44$, $p = .66$).

Conflict adaptation analysis. Medians of response times for correctly solved trials and percentage of hits were calculated for each participant in each condition: incongruent trials preceded by congruence (*cI*), congruent trials preceded by congruence (*cC*), incongruent trials preceded by incongruity (*iI*) and congruent trials preceded by incongruity (*iC*). Then, these means were used to calculate the interference effect preceded by congruence (*cI-cC*) and the interference effect preceded by incongruity (*iI-iC*). Similarly, hit rates were calculated for the interference effect preceded by congruence (*cC-cI*) and preceded by incongruity (*iC-iI*). A potential confound of examining the neural and behavioral reflections of conflict adaptation effects is the inclusion of error and post-error trials [42]. Error trials are frequently associated with faster RTs [56], while post-error trials are associated with reliable RT slowing [57]. In order to separate the effect of error processing from the conflict adaptation processes, error and post-error trials were excluded from both the conflict monitoring and the conflict adaptation analyses.

Response time and hit rate data were submitted to a repeated measures ANOVA taking *Previous congruence* (congruent and incongruent) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor. The *F* value, the degrees of freedom, the probability level, and the η^2 effect size index are given.

Regarding response times, the ANOVA showed a significant main effect of *Previous congruence* ($F(1,32) = 4.16$, $p = .04$, $\eta^2 = .11$), with the interference effect being higher when preceded by congruence (mean = 64.57, SEM = 5.89) than when preceded by incongruity (mean = 51.33, SEM = 5.48). The main effect of *Group* was also significant ($F(1,32) = 4.15$, $p = .05$, $\eta^2 = .11$), showing that, regardless of the congruence of the previous trial, the HMA group was slower (mean = 67.50, SEM = 6.61) than the LMA one (mean = 48.41, SEM = 6.61). The *Previous congruence* × *Group* interaction was far from significant ($p = .64$).

As for percentage of hits, the ANOVA showed a significant main effect of *Previous congruence* ($F(1,32) = 5.31$, $p = .02$, $\eta^2 = .14$), with the interference effect being higher when preceded by congruence (mean = 21.64, SEM = 2.30) than when preceded by incongruity (mean = 17.22, SEM = 2.25). The main effect and interactions with *Group* were far from significant (all *p* values above.57).

Response times and percentage of hits for each group for the conflict monitoring and conflict adaptation effects are shown in Table 2.

Event-Related Potentials

ERPs time-locked to the presentation of the stimuli were averaged for each participant. As in the behavioral analysis, error and post-error trials were not included in the analysis. The

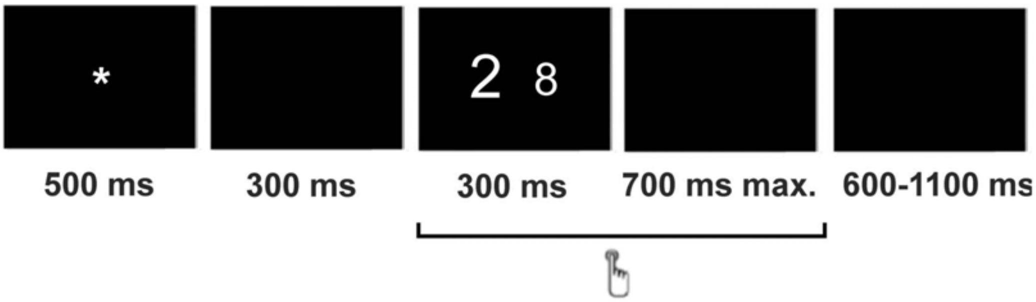

Figure 1. Structure and timing of a trial of the numerical Stroop task using an incongruent stimulus.
doi:10.1371/journal.pone.0099579.g001

Table 2. Response times (mean of medians) and accuracy (percentage of hits) (SEM in brackets) for the LMA and HMA groups for conflict monitoring and for conflict adaptation effects.

		Conflict monitoring	**Conflict adaptation**	
		Interference	**Interference preceded by congruence**	**Interference preceded by incongruity**
Response time	LMA	52.02 (5.30)	56.52 (7.13)	40.29 (5.26)
	HMA	72.50 (8.15)	72.61 (9.37)	62.38 (9.62)
Hit rates	LMA	21.62 (2.83)	23.08 (3.36)	17.56 (2.69)
	HMA	20.00 (2.32)	20.22 (3.13)	16.89 (3.61)

Note. Conflict monitoring: for response time: interference = incongruent – congruent; for hit rates: interference = congruent – incongruent. Conflict adaptation: for response time: interference preceded by congruence = *cI-cC;* interference preceded by incongruity = *iI-iC;* for hit rates: interference preceded by congruence = *cC-cI;* interference preceded by incongruity = *iC-iI.*

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averages were constructed from −100 to 1000 ms epochs relative to stimulus onset. A 100-ms window prior to the stimulus (−100 to 0 ms) served as the baseline. Trials with voltages exceeding ±75 µV in any electrode were excluded from the ERP average. Only trials correctly answered were included. For the conflict monitoring analysis, two averages were calculated per participant: one for congruent trials and another for incongruent trials. As in previous investigations [19,29,32,35,58], interference was defined as the incongruent minus the congruent conditions. For the conflict adaptation analysis, four averages were calculated per participant: incongruent trials preceded by incongruity (*iI*), incongruent trials preceded by congruence (*cI*), congruent trials preceded by incongruity (*iC*), and congruent trials preceded by congruence (*cC*). The interference effect preceded by congruence was calculated by subtracting the cC trials from the cI trials (*cI-cC*), while the interference effect preceded by incongruity was calculated by subtracting the iC trials from the *iI* trials (*iI-iC*).

Conflict monitoring analysis. For all the ANOVAs performed in this study, the Greenhouse-Geisser correction [59] for violations of sphericity was applied when appropriate. The *F* value, the uncorrected degrees of freedom, the probability level following correction, the ε value (when appropriate), and the η^2 effect size index are given. Statistically significant interactions were identified by tests of simple effects, with the Bonferroni correction being applied in order to control for the increase in type I errors.

P1 component. A repeated measures ANOVA was performed for the incongruent-congruent difference of mean amplitudes in the 100–150 ms window at occipital sites (O1, O2 and O3) taking *Laterality* (three levels from left to right) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor.

The ANOVA showed no significant main effect or interaction (all *p* values above.27).

N450. A repeated measures ANOVA was performed for the incongruent-congruent difference of mean amplitudes in the 350–500 ms window at fronto-central (Fc1, Fcz, and Fc2) and central (C1, Cz and C2) sites taking *Frontality* (fronto-central and central) and *Laterality* (three levels from left to right) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor. This time window was chosen based on previous literature and on the visual inspection of ERP waves.

The ANOVA showed no *Group* significant main effect or interaction (all *p* values above.17). Figure 2 shows raw waves (A) and topographic maps (B) for the N450 component for the LMA and HMA groups, where the lack of differences between groups is shown. The mean amplitudes for N450 in the 350–500 ms window are shown in Table 3.

Conflict-SP. A repeated measures ANOVA was performed for the incongruent – congruent differences of mean amplitudes in the 550–750 ms window at central sites (C1, Cz and C2) taking *Laterality* (three levels from left to right) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor. This time window was chosen based on previous literature and on the visual inspection of ERP waves.

The overall ANOVA revealed a marginally significant main effect of *Group* ($F(1,32) = 2.79$, $p = .09$, $\eta^2 = .08$), with the HMA group showing a greater positivity (e.g., at Cz mean = .80 µV, SEM = .16) than the LMA one (mean = .50 µV, SEM = .10). Figure 3 shows raw waves (A) and topographic maps (B) for Conflict-SP for the HMA and LMA groups, showing greater amplitude for the HMA group as compared to the LMA one. The mean amplitudes for Conflict-SP in the 550–750 ms window are shown in Table 3.

Conflict adaptation analysis. *P1 component.* A repeated measures ANOVA was performed for the mean amplitude of the interference effect preceded by congruence (*cI-cC*) and preceded by incongruity (*iI-iC*) in the 100–150 ms window at occipital sites (O1, Oz and O2), taking *Previous congruence* (congruent and incongruent) and *Laterality* (three levels from left to right) as within-subject factors and *Group* (LMA and HMA) as the between-subjects factor.

The ANOVA showed no significant main effect or interaction (all *p* values above.24).

N450. A repeated measures ANOVA was performed for the mean amplitude of the interference effect preceded by congruence (*cI-cC*) and preceded by incongruity (*iI-iC*) in the 350–500 ms window at fronto-central (Fc1, Fcz, and Fc2) and central (C1, Cz and C2) sites, taking *Previous congruence* (congruent and incongruent), frontality (fronto-central and central) and *Laterality* (three levels from left to right) as within-subject factors and *Group* (LMA and HMA) as the between-subjects factor.

The ANOVA showed a significant main effect of *Previous congruence* ($F(1,32) = 5.61$, $p = .02$, $\eta^2 = .14$), with the amplitude of N450 being more negative when preceded by congruence (mean = −.69, SEM = .11) than when preceded by incongruity (mean = −.33, SEM = .13). The *Group x Frontality* interaction was also significant ($F(1,32) = 3.89$, $p = .05$, $\eta^2 = .10$). In order to analyze this interaction, separate ANOVAS were performed at fronto-central and central sites. While no *Group* main effect or interactions emerged at fronto-central sites (all *p* values above.31), a significant *Group x Previous congruence* interaction ($F(1,32) = 3.95$, $p = .05$, $\eta^2 = .11$) was found at central sites. This interaction showed that for the LMA group, the N450 was more negative when preceded by congruence (mean = −.83 µV, SEM = .15)

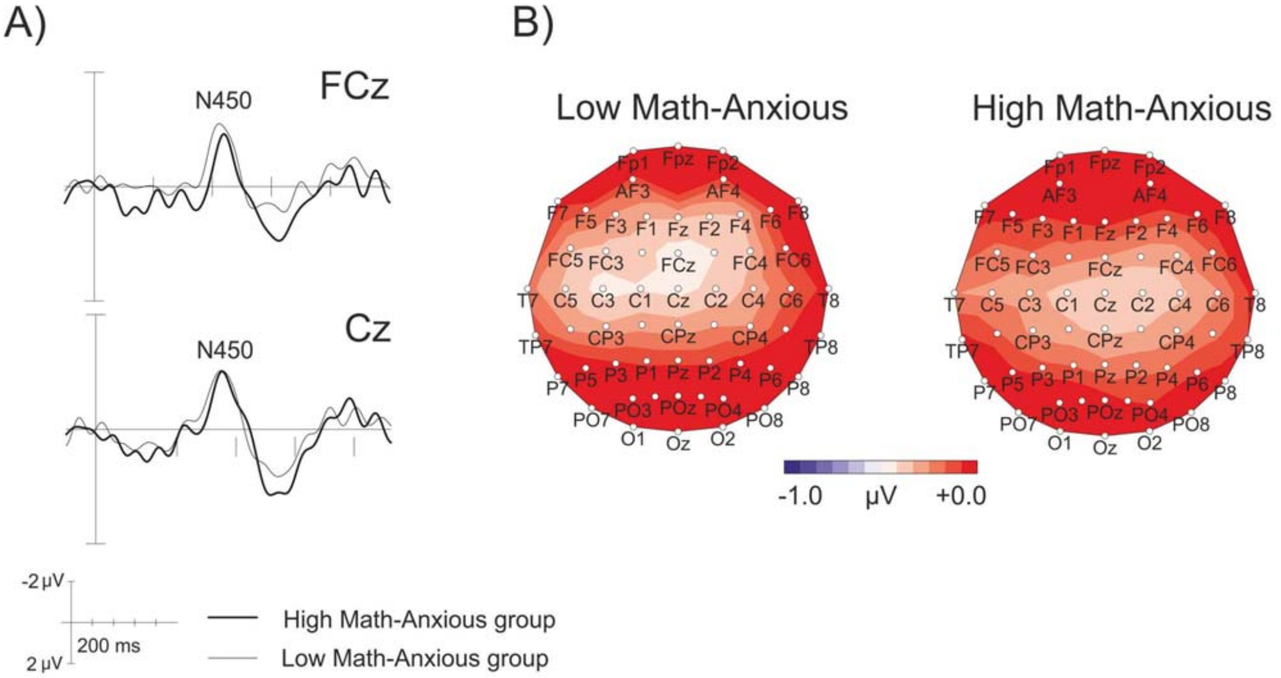

Figure 2. Grand average waveforms at FCz and Cz for the N450 component, showing the interference effect (incongruent-congruent) in the LMA and HMA groups (A); and the scalp topography of the N450 component, showing the interference effect in the 350–500 ms window for the LMA and HMA groups (B).
doi:10.1371/journal.pone.0099579.g002

than when preceded by incongruity (mean = −.13 µV, SEM = .19) ($p = .004$), while no differences were found for the HMA group ($p = .80$). Figure 4 shows raw waves (A) and topographic maps (B) for N450 elicited for the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*) for the LMA and the HMA groups. This figure clearly shows a greater N450 component for the interference effect preceded by congruence than when preceded by incongruity only for the LMA group. The mean amplitudes for N450 in the 350–500 ms window are shown in Table 3.

Conflict-SP. A repeated measures ANOVA was performed for the mean amplitude of the interference effect preceded by congruence (*cI-cC*) and preceded by incongruity (*iI-iC*) in the 550–750 ms window at central sites (C1, Cz, and C2), taking *Previous congruence* (congruent and incongruent) and *Laterality* (three levels from left to right) as within-subject factors and *Group* (LMA and HMA) as the between-subjects factor.

The ANOVA showed a significant *Previous congruence* × *Group* interaction ($F(1,32) = 4.20$, $p = .04$, $\eta^2 = .11$), with a greater amplitude for the interference effect preceded by congruence (mean = 1.16, SEM = .28) than when preceded by incongruity (mean = .25, SEM = .19) for the HMA group ($p = .01$), but no differences for the LMA one ($p = .84$). Apart from the marginally significant main effects of *Previous congruence* ($F(1,32) = 3.15$, $p = .08$, $\eta^2 = .09$) and *Group* ($F(1,32) = 3.22$, $p = .08$, $\eta^2 = .09$), all the other effects and interactions were not significant (all p values above.15). Figure 4 shows raw waves (A) and topographic maps (B) for Conflict-SP for the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*) for the LMA and the HMA groups. The figure clearly shows that the HMA group showed a more positive amplitude for the interference effect preceded by congruence than when preceded by incongruity, while no differences emerged for the LMA group. The mean amplitudes for Conflict-SP in the 550–750 ms window are shown in Table 3.

Table 3. Means and standard errors (in brackets) for N450 and Conflict-SP for conflict monitoring and conflict adaptation effects in the LMA and the HMA groups.

		Conflict monitoring	**Conflict adaptation**	
		Interference	**Interference preceded by congruence**	**Interference preceded by incongruity**
N450	LMA	−.67 (.16)	−.83 (.15)	−.13 (.19)
	HMA	−.53 (.14)	−.66 (.22)	−.64 (.24)
Conflict-SP	LMA	.50 (.10)	.38 (.18)	.41 (.20)
	HMA	.80 (.16)	1.16 (.28)	.25 (.19)

Note. Interference: incongruent – congruent; Interference preceded by congruence: (*cI-cC*); Interference preceded by incongruity: (*iI-iC*); N450: mean amplitude at Cz for the 350–500 ms window; CSP: mean amplitude at Cz for the 550–750 ms window.
doi:10.1371/journal.pone.0099579.t003

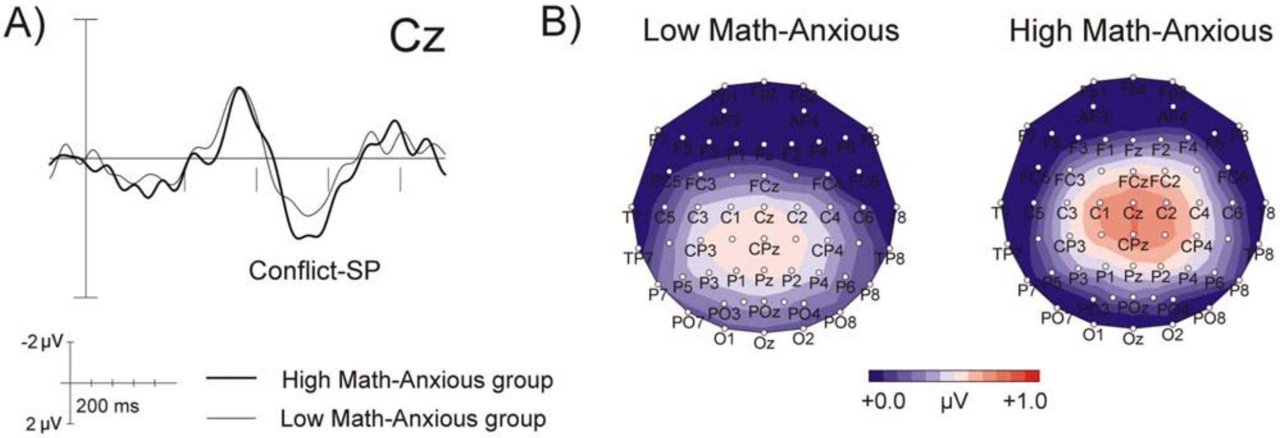

Figure 3. Grand average waveforms at Cz for Conflict-SP, showing the interference effect (incongruent-congruent) in the LMA and HMA groups (A); and the scalp topography of Conflict-SP, showing the interference effect in the 550–750 ms window for the LMA and HMA groups (B).
doi:10.1371/journal.pone.0099579.g003

Correlational Analyses

Relation between math anxiety and behavioral measures. Participants' scores on the sMARS test were correlated with the interference effect shown in behavioral measures for the conflict monitoring and conflict adaptation effects. Results are shown in Table 4. This table shows that the higher the level of math anxiety, the greater the interference in response times for the current trial and the greater the interference in response times when preceded by incongruity.

Relation between math anxiety and ERP measures. The sMARS scores were also correlated with the mean amplitude of N450 and Conflict-SP for the conflict monitoring and conflict adaptation effects. Results are shown in Table 5. This table shows that the higher the level of math anxiety, the greater the amplitude of the Conflict-SP when preceded by congruence.

Relation between behavioral and ERP measures. Finally, ERP measures of conflict monitoring and conflict adaptation were correlated with the interference effect shown in behavioral measures for these effects. Results are shown in Table 6. This table shows that the greater the interference in hit rates (more errors committed in the incongruent condition than in the congruent one), the more negative the amplitude of the N450 and the more positive the amplitude of the Conflict-SP for the interference effect preceded by congruence.

Discussion

This study aimed to investigate numeric conflict monitoring and conflict adaptation in high math-anxious individuals with the help of the ERP technique, in order to investigate further whether math anxiety is related to difficulties in early and/or later stages of conflict processing, and to better understand math anxiety-related differences in the execution of attentional control when conflict is encountered in processing. As far as we know, this is the first time that numeric conflict monitoring and adaptation are studied with ERPs in math anxious individuals. To this end, we formed two groups that were extreme in math anxiety, but that did not differ in trait anxiety, state anxiety or math ability, enabling us to rule out the possibility that the expected differences between groups could be attributed to these variables. Both groups had to solve a numerical Stroop task involving congruent and incongruent trials in equal proportion. We expected to reproduce previous research by finding a greater interference in response times for the HMA group. The ERP technique helped to identify two conflict-related ERP components enabling us to determine whether math anxiety is related to a first stage of conflict detection (i.e., N450) and/or to a later response-related (i.e., Conflict-SP) stage of conflict processing. Moreover, conflict adaptation analysis provides useful information regarding possible variations in attentional control in math anxious individuals depending on the congruence of the previous trial, as previously suggested for trait anxiety [45,48].

Regarding behavioral measures, and consistent with previous studies in math anxiety, a greater interference effect was found in response times for the HMA group as compared to the LMA one [17,23]. This corroborates the main claims of the ACT [9] arguing that high anxious individuals are characterized by a greater influence of the stimulus-driven attentional system relative to the goal-directed attentional system. In this way, according to this theory, HMA individuals would be more influenced by the distractor dimension of the stimuli (i.e., number size) interfering with the task-relevant dimension of the task (i.e., numerical magnitude), which would explain why they needed more time to solve trials presenting a stimuli-response conflict than their LMA counterparts. Also in this respect, we found a significant positive correlation between interference in response times and math anxiety; the greater the level of math anxiety, the more time needed to respond to incongruent trials as compared to congruent ones. Moreover, in accordance with the ACT [9] and the original PET [10], the effects of math anxiety were shown on response times (i.e., processing efficiency) but not on hit rates (i.e., performance effectiveness), given that anxiety is considered not to directly affect the level of performance on a task, but to reduce the efficiency with which the task is solved.

Regarding electrophysiological data, we were able to replicate the results of previous studies by identifying two ERP components crucially linked to stimulus-response conflicts in the Stroop task, namely, N450 and Conflict-SP. Our conflict monitoring analysis showed that math-anxious individuals did not differ in a first conflict detection stage of processing, given that there were no differences between groups for the N450 component (neither for an even earlier P1 component). However, the HMA group did show a tendency for greater Conflict-SP amplitude than the LMA group. It is not easy to say what this difference is telling us, given that this component has been related with a very wide range of

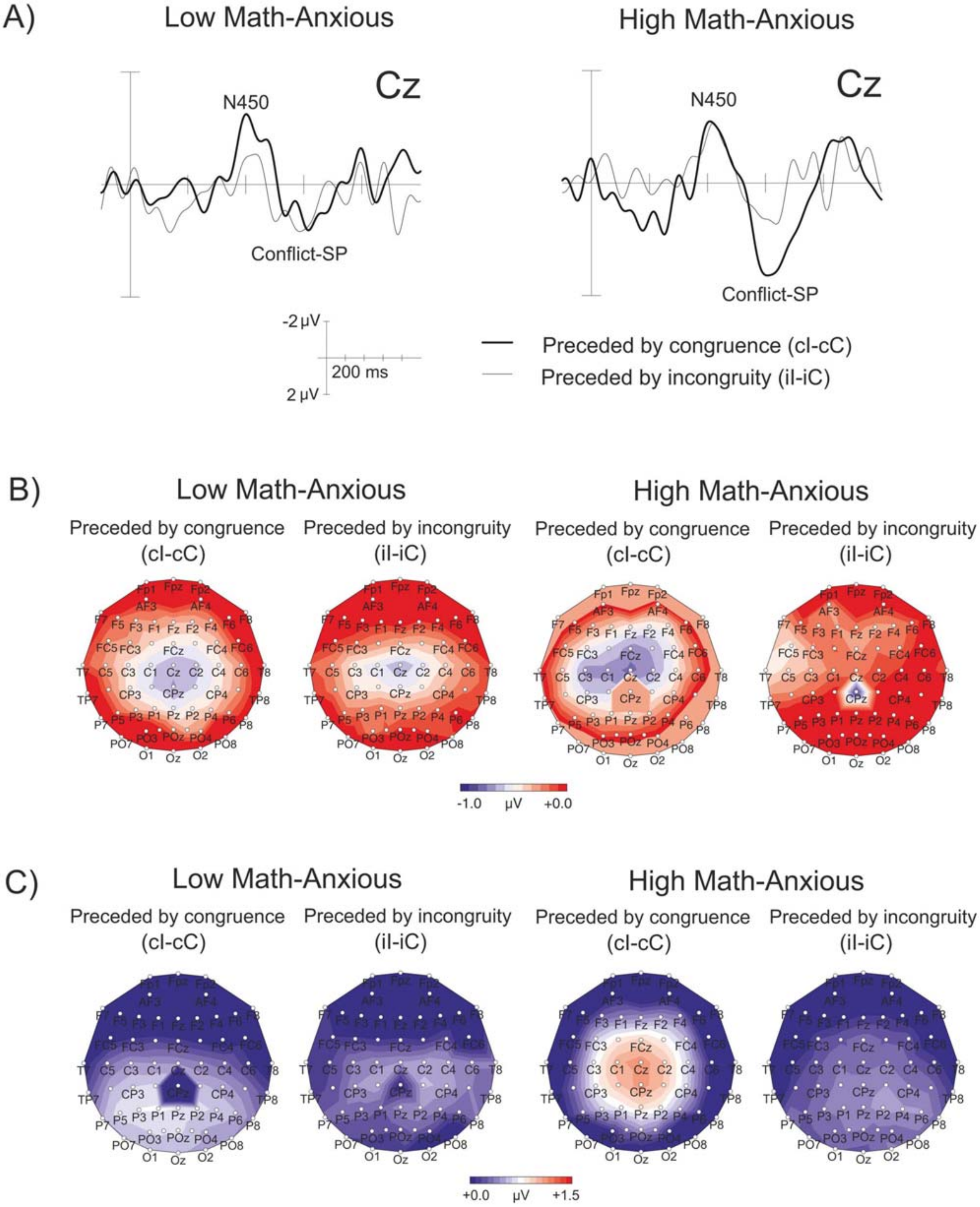

Figure 4. Grand average waveforms at Cz for the N450 component and for the Conflict-SP, showing the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*) for the LMA and HMA groups (A) the scalp topography of the N450 component, showing the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*) in the 350–500 ms window for the LMA and HMA groups (B) and the scalp topography of Conflict-SP, showing the interference effect preceded by congruence (*cI-cC*) and by incongruity (*iI-iC*) in the 550–750 ms window for the LMA and HMA groups (C).
doi:10.1371/journal.pone.0099579.g004

Table 4. Pearson correlation coefficients between the sMARS scores and behavioral measures for conflict monitoring and conflict adaptation for the whole sample (n = 34).

	Conflict monitoring		Conflict adaptation			
	Reaction time	Accuracy	Reaction time		Accuracy	
	Interference	Interference	Interference preceded by congruence	Interference preceded by incongruity	Interference preceded by congruence	Interference preceded by incongruity
sMARS	.34 *	−.05	.16	.37 *	−.09	−.01

Note. * $p<.05$.

doi:10.1371/journal.pone.0099579.t004

cognitive processes such as general preparation [33], response selection [18], conflict processing [29,60], and execution of top-down control [38]. Nevertheless, conflict adaptation analysis can help us to clarify the evidence on cognitive function signaled by this Conflict-SP, and thus to give support to one of these possible interpretations. Conflict adaptation effects were first reported by Gratton et al. (1992), who found that the interference effect was enhanced when preceded by congruent trials [40]. The conflict monitoring model explains this finding as an enhancement in attentional control when incongruity is found. If attentional control is enhanced in the previous trial, the task-irrelevant dimension of the stimulus has less influence, and thus the interference effect is reduced. We were able to replicate this effect in our data by finding larger response times and reduced hit rates for the interference effect preceded by congruence (which does not enhance attentional control) as compared to the interference effect preceded by incongruity (considered to enhance attentional control). Nevertheless, in line with previous evidence on trait anxiety, no significant group differences were obtained for these behavioral measures of conflict adaptation [48]. The reason may be that behavioral measures often provide very indirect evidence of internal processes such as cognitive control, which can sometimes only be detected using more sensitive techniques, such as ERPs.

In fact, ERPs showed differences in conflict adaptation between math anxious groups for the N450. More specifically, we found that while the LMA group showed a more negative N450 for the interference effect preceded by congruence than when preceded by incongruity, the HMA group showed no difference in this component in relation to the congruence of the previous trial. Previous evidence has shown that the N450 shows greater amplitudes when the level of conflict is higher [31]. Similarly, we found a negative correlation between the interference in hit rates and the amplitude of the N450 when preceded by congruence, showing that as the level of interference increased, the N450 became more negative. These results suggest that the LMA group experienced a higher level of conflict due to the interference effect preceded by congruence than when preceded by incongruity. In other words, while the LMA group showed the expected conflict adaptation effect pattern (i.e. greater interference when preceded by congruence), the HMA group did not show this effect at this first stage of conflict processing.

Previous evidence has suggested that the N450 component showed no variation with previous trial congruence [38]. Using a color-naming Stroop task in normal participants, Larson et al. (2009) found that the N450 component did not vary according to the congruence of the previous-trial, and they proposed that this component reflected neural processes that were more automatic, regardless of the amount of top-down control needed during a particular trial. In contrast, we found that the congruence of the previous trial did modulate the amplitude of this component in LMA individuals, suggesting that it is modulated by variations in attentional control, and therefore, that it reflects more than a simple automatic process [48]. Similarly, using a gender discrimination Stroop task with the help of the ERP technique, Osinsky et al. (2010) also found a modulation of the N450 amplitude with variations of the congruence of the previous trial for trait anxiety; more specifically, they obtained a greater N450 component for the interference effect preceded by incongruity than when preceded by congruence for the high trait anxious group [48]. They tentatively interpreted this finding as indicating a reactive engagement of the conflict monitor as a direct response to an acute need for top-down guidance. In contrast, we obtained a normal and expected conflict adaptation effect (greater N450 for the interference effect preceded by congruence) for the LMA group but no conflict adaptation at all for the HMA group.

Conflict adaptation analysis also showed very interesting effects for the Conflict-SP. More specifically, we found that, while no differences were obtained for the LMA group depending on the congruence of the previous trial, the HMA group showed greater

Table 5. Pearson correlation coefficients between the sMARS scores and ERP measures for conflict monitoring and conflict adaptation for the whole sample (n = 34).

	Conflict monitoring		Conflict adaptation			
	N450	Conflict-SP	N450		Conflict-SP	
	Interference	Interference	Interference preceded by congruence	Interference preceded by incongruity	Interference preceded by congruence	Interference preceded by incongruity
sMARS	.10	.30	.10	−.29	.42*	−.11

Note. * $p<.05$; N450: mean amplitude at Cz for the 350–500 ms; Conflict-SP: mean amplitude at Cz for the 550–750 ms window.

doi:10.1371/journal.pone.0099579.t005

Table 6. Pearson correlation coefficients between behavioral and ERP measures for conflict monitoring and conflict adaptation for the whole sample (n = 34).

Behavioral measures			**ERP measures**					
			Conflict Monitoring		**Conflict Adaptation**			
			N450	**Conflict-SP**	**N450**		**Conflict-SP**	
			Interference		**Interference preceded by congruence**	**Interference preceded by incongruity**	**Interference preceded by congruence**	**Interference preceded by incongruity**
Conflict Monitoring	Reaction time	Interference	.02	.13	.06	−.06	.22	.24
	Accuracy	Interference	−.30	.48*	−.36*	−.10	.43*	.03
Conflict Adaptation	Reaction time	Interference preceded by congruence	.15	.002	.20	.03	.04	.24
		Interference preceded by incongruity	−.11	.08	−.13	−.13	.23	.11
	Accuracy	Interference preceded by congruence	−.34	.35	−.32	−.10	.43*	.003
		Interference preceded by incongruity	.04	.50*	−.17	.009	.33	.05

Note. * $p < .05$; N450: mean amplitude at Cz for the 350–500 ms; Conflict-SP: mean amplitude at Cz for the 550–750 ms window.

doi:10.1371/journal.pone.0099579.t006

Conflict-SP amplitude for the interference effect preceded by congruence than when preceded by incongruity. This result suggests that the tendency for greater Conflict-SP amplitude for the HMA group in the conflict monitoring analysis (current trial congruence effects) might be due to the greater amplitude for this component when it is preceded by congruence, while the interference effect preceded by incongruity shows a similar pattern for the LMA group. This result gives support to previous evidence suggesting that Conflict-SP reflects controlled processes that adapt to the level of control necessary to accurately complete the trial [38]. Moreover, a significant positive correlation emerged between math anxiety scores and Conflict-SP for the interference effect preceded by congruence, showing that the higher the level of math anxiety, the greater the amplitude at this later stage of conflict processing.

These results give support to the DMC account, suggesting that high anxious individuals are characterized by a tendency to exert attentional control in a reactive way, that is, only when conflict is encountered in processing. On the other hand, low anxious individuals are considered to exert attentional control in a proactive way, by maintaining task goals over time. Previous investigations have given support to this account. For example, Fales et al. (2008) carried out a mixed blocked/event-related fMRI design to track transient (i.e. reactive) and sustained (i.e. proactive) activity in the dorsolateral prefrontal cortex (DLPFC) (an area considered to support cognitive control) while high and low anxious participants performed a working memory task. Results showed that high and low anxious individuals made strikingly different use of cognitive and default-network circuitry during the performance of a cognitive task. More concretely, they reported a positive correlation between trait anxiety and transient (i.e. reactive) activation of the DLPFC during working memory performance [47]. Similarly, using a gender discrimination task including congruent and incongruent face-word pairings and incorporating stimuli presenting only the task-relevant (face) and the task-irrelevant (word) dimensions of the stimuli, Osinsky et al. (2012) found that after incongruent trials, high trait-anxious individuals showed higher processing of the task-relevant dimension of the stimulus and suppressed processing of the task-irrelevant dimension of the stimulus, which also suggested a conflict-driven reactive recruitment of cognitive control in high trait-anxious individuals [45]. Our study, by finding that HMA individuals only exert attentional control after incongruent trials (Conflict-SP showed enhanced amplitude for the interference effect preceded by congruence), extends these findings to the field of math anxiety.

Moreover, according to the DMC model, this difference in the way attentional control is exerted depending on the level of anxiety has consequences on the susceptibility to distraction. In this way, HMA individuals, by exerting attentional control only when conflict is encountered in processing, would be more easily influenced by bottom-up input (i.e., the ACT's stimulus-driven attentional system) [13], and thus would be more easily distracted. On the other hand, LMA individuals, by sustaining task requirements or goals over time, would show more effective top-down control of processing (i.e., the ACT's goal-directed attentional system) [13] and thus would be less influenced by distraction. Consequently, the greater interference effect found for response times in the HMA group might be explained by differences in the way attentional control is exerted, by making HMA individuals more vulnerable to task-irrelevant information.

Two important aspects of this study deserve mention. The state anxiety measure we reported in the Participants section was obtained during the screening phase of this study (and not after the experimental task performed in the lab). The STAI was always administered after the math ability and the sMARS tests. Despite going through these math-related situations, the LMA and HMA groups did not differ in terms of their state-anxiety scores. However it might still be the case that they differed during the experimental task, and so we cannot rule out the possibility that our results show some effect of state anxiety apart from the effect of (trait) math anxiety. Second, beyond the congruence effect generated by presenting pairs of numbers showing a conflict between numerical magnitude and physical size, number pairs also differed in their distance from each other, i.e. being close (distance 1; e.g. 1–2 and 8–9) or further away (distance 7; e.g. 1–8 and 2–9). Conceivably, it could be that the distance effect introduced some undesired variability in our data. However, an additional analysis was performed for response times to test this possibility, and the results showed the expected *distance effect* in our data, distance 1 requiring more time than distance 7, but this effect did not affect the two groups in different ways (no significant group main effect or interaction emerged), suggesting that this effect cannot explain our findings.

Although our math anxious individuals did not differ in their conflict monitoring (only considering the effect of the current trial), they showed very interesting differences in their responses and adaptation to the congruence of the previous trial. LMA individuals showed a conflict adaptation effect in the first stage of conflict processing (N450) followed by a proactive execution of attentional control, which was exerted for the interference effect preceded both by congruence and by incongruity. In contrast, high math-anxious individuals were characterized by an absence of a conflict adaptation effect in the first stage of conflict processing followed by a reactive and compensatory recruitment of control resources and goal-directed attention, which was exerted only when they had previously been exposed to stimuli presenting conflicting information. In view of previous evidence claiming that a reactive execution of attentional control contributes to a greater susceptibility to distraction, and given that, in our study, this lack of enhancement in attentional control after congruent trials was related to a failure to overcome conflict (i.e. after congruence, the greater the Conflict-SP amplitude, the greater the interference in accuracy), this difference in the execution of attentional control after conflict detection may very well explain the differences between low and high math-anxious individuals when processing numerical conflict.

As far as we know, this study is the first attempt to identify the electrophysiological correlates of conflict monitoring and conflict adaptation in math anxious individuals, while controlling for general anxiety and math ability. We have replicated previous studies showing greater numeric interference in response times for the HMA group, suggesting that math anxiety affects higher-order functions of cognitive control, making task-irrelevant information more intrusive for this group as compared to the LMA one [17,23]. It is worth mentioning that, in our study, HMA individuals showed greater susceptibility to distraction in a task involving conflict between numerical magnitude and physical size. Nevertheless, this susceptibility to distraction is not limited to this kind of information, but also extends to the distractor effect that internal stimuli, such as worrying thoughts and ruminations, have on working memory [9]. As a consequence, HMA individuals may also be more vulnerable to these kinds of thoughts that attract attention away from the task and impair performance. The effects of distraction could be especially detrimental in the learning of mathematics, given its cumulative nature, one concept building on the next. For this reason, attentional control deficit and distractibility in high math anxious individuals constitutes a key aspect deserving further research.

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Author Contributions

Conceived and designed the experiments: MINP. Performed the experiments: MSP. Analyzed the data: MSP. Contributed reagents/materials/analysis tools: MINP AC. Wrote the paper: MSP. Correction of the manuscript: MINP AC.

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Study IV

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Abnormal Error Monitoring in Math-Anxious Individuals: Evidence from Error-Related Brain Potentials

Macarena Suárez-Pellicioni[1,2], María Isabel Núñez-Peña[1,2*], Àngels Colomé[2,3]

1 Department of Behavioural Sciences Methods, University of Barcelona, Barcelona, Spain, **2** Institute for Brain, Cognition and Behaviour, University of Barcelona, Barcelona, Spain, **3** Department of Basic Psychology, University of Barcelona, Barcelona, Spain

Abstract

This study used event-related brain potentials to investigate whether math anxiety is related to abnormal error monitoring processing. Seventeen high math-anxious (HMA) and seventeen low math-anxious (LMA) individuals were presented with a numerical and a classical Stroop task. Groups did not differ in terms of trait or state anxiety. We found enhanced error-related negativity (ERN) in the HMA group when subjects committed an error on the numerical Stroop task, but not on the classical Stroop task. Groups did not differ in terms of the correct-related negativity component (CRN), the error positivity component (Pe), classical behavioral measures or post-error measures. The amplitude of the ERN was negatively related to participants' math anxiety scores, showing a more negative amplitude as the score increased. Moreover, using standardized low resolution electromagnetic tomography (sLORETA) we found greater activation of the insula in errors on a numerical task as compared to errors in a non-numerical task only for the HMA group. The results were interpreted according to the motivational significance theory of the ERN.

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* E-mail: inunez@ub.edu

Introduction

Math anxiety has been defined as a feeling of tension, apprehension or even dread, ranging from mild discomfort to extreme avoidance [1], which interferes with the ordinary manipulation of numbers and the solving of math problems [2]. The 2003 Program for International Student Assessment (PISA) report showed that more than 50% of 15-year-old students had feelings of insecurity and emotional stress when they were asked to solve mathematical problems. Similarly, behavioral studies have shown that math anxiety has a negative effect on a wide range of numerical and mathematical tasks, ranging from simple tasks like counting objects [3] to more complex arithmetical problems involving carrying [4]. Feelings of this kind make high math anxious individuals avoid situations that are math-intensive, and thus, to avoid educational tracks and career paths that depend on this discipline. Given the negative impact of math anxiety on mathematical learning and professional development, its study has emerged as a topic deserving intensive investigation. However, despite the increasing number of studies on math anxiety, error monitoring processing in this type of anxiety has not been assessed. The ability to learn from mistakes and to use that knowledge to guide future behavior is a critical cognitive skill, given that in many situations people rely upon internal self-monitoring to determine when their behavior is adequate or when adjustments need to be made. Studying how math anxious individuals perceive their self-generated errors, how they respond or adjust to them and how they perceive a numerical error as compared to a non-numerical one constitutes a very rich source of information that can improve our understanding of their difficulties with the subject and may identify a possible factor influencing the development and persistence of math anxiety.

A marker of performance monitoring that can be observed in brain activity is a very early negative component called error-related negativity (ERN) [5] or *error negativity* (Ne) [6]. The ERN is a response-locked event-related brain potential (ERP), observed as a sharp negative deflection at fronto-central recording sites along the midline (FCz or Fz electrode position) approximately 50-150 ms after an error is committed [5,7]. A wealth of data suggests that the ERN is generated in the Anterior cingulate cortex (ACC), a region of the medial prefrontal cortex that is richly interconnected with both limbic and frontal regions of the brain [6,8–11]. The precise cognitive mechanisms that generate the ERN are under debate, but the principal theories explaining its functional significance suggest that it reflects the detection of a mismatch between the representations of the actual and intended responses (*Mismatch theory*) [6], conflict monitoring in the ACC arising from multiple simultaneously active response tendencies (*Conflict monitoring theory*) [12] or the disinhibition of the ACC by dopamine neurons, which signal events as worse than anticipated (*Reinforcement and learning-based theories*) [13]. The principal shortcoming of these theories is that they do not account for motivational and individual differences. This limitation is overcome by the *motivational significance theory*, which suggests that the ERN may reflect error detection that is utilized for motivational ends; in this case, the amplitude of the ERN might be related to the significance of an error. For example, the ERN is enhanced when accuracy is emphasized over speed [5], when errors are associated with a high monetary risk or when errors are committed during social evaluation [14]. These and other studies have shown that more significant errors result in a larger ERN. Furthermore, this theory is often discussed in terms of affective processes. According to this interpretation, the ERN may be influenced by an individual's emotional reaction to an error [15]. The idea is that affective evaluation occurs during error detection and that this evaluation varies along a continuum related to the distress caused by the commission of the error [16]. In fact, individuals with certain personality traits, characterized by increased sensitivity to errors, produce increased ERNs [17]. For example, enhanced ERN was found in patients with obsessive-compulsive disorder (OCD) [18,19], in undergraduate students with high obsessive compulsive characteristics [20], in patients with generalized anxiety disorder (GAD) [21], in undergraduates with high scores on measures of general anxiety and worry [22] and in participants scoring high on negative affect [23,24].

The counterpart of the ERN in correct trials is called correct-response negativity (CRN) [25]. The CRN is a small ERN-like component with the same temporal characteristics and scalp topography as the ERN. While its precise functional significance remains unclear, it may reflect a response comparison process [15], uncertainty about a correct response [25] or coactivation of correct and error responses [24]. The association between anxiety and this component is not yet clear. While several studies have found an enhancement in the ERN with higher levels of anxiety but no similar effect on the CRN [18,19], others have found an enhancement in both the ERN and CRN components [20,22,23,26–28]. While the first group of authors attribute their results to abnormal error monitoring (enhanced vigilance specifically for errors), the second group propose the enhancement of the two components as a sign of abnormal response monitoring in general. Some studies aiming to localize the source of this component have found that the CRN and the ERN represent the activity of the same underlying neuronal network [29,30] and thus, ostensibly reflect the same process. Nevertheless, other studies have found that the neural generators of the CRN were different and involved more posterior cingulate regions [31].

Error-related positivity (Pe) [32] appears after the ERN. This is a positive-going deflection in the waveform that is present between 200 and 400 ms after an error is committed, which exhibits a more posterior and central scalp distribution (maximum at Cz) than the ERN. It is also present after correct trials, but with a considerably attenuated amplitude [21,26,31]. The functional significance of the Pe is not as well understood as the ERN, but it has been principally associated with error awareness [33]. It has been shown that when errors are not recognized, the ERN amplitude and ACC activity remain unchanged, but the Pe amplitude is significantly lower than in recognized errors [34]. There are very few studies relating this component with anxiety and, generally, no significant differences have been found [19,21,35]. Nevertheless, other studies have suggested smaller Pe in high-anxious individuals [18,20]. The putative generator of Pe has also been estimated within the ACC region, the cingulate gyrus [36], and more posterior cingulate regions [37]. The exact distinction between ERN and Pe remains to be clarified in terms of both functional significance and anatomical sources.

In the present study, we investigated differences in error monitoring as a function of math anxiety. Our objective was to help determine a possible factor in the development and maintenance of math anxiety and to further the understanding of the impairments experienced by the individuals who suffer from it. As far as we know, no study to date has investigated error-related brain potentials in high math-anxious individuals. To do so, we formed two groups with extreme levels of math anxiety, but who did not differ in terms of trait or state anxiety; consequently, group differences could not be attributed to general anxiety. Traditionally, error-related ERP components are elicited by having participants engage in a speeded response task. A good candidate is the Stroop task, given that participants have to deal quickly with contradictory information that makes them commit a sufficient number of errors. In our experiment participants performed a numerical Stroop task [38] (salient for the high math-anxious group) and a modified classical Stroop task (control task) [18]. We recorded the ongoing EEG and subsequently examined brain activity time-locked to both error responses (for the ERN) and correct responses (for the CRN).

Based on the association between anxiety and internal error monitoring, enhanced ERN was expected in high math-anxious individuals only on the numerical Stroop task, which is the more salient task for this group. Moreover, given previous evidence of a significant negative correlation between the magnitude of the ERN enhancement and the severity of GAD patients [21], we expected to find the same significant negative correlation between the ERN amplitude and the self-reported level of math anxiety. We also analyzed whether math anxiety was associated only with erroneous responses, which would indicate abnormal error monitoring (enhanced vigilance specifically for errors), or with both error and correct trials (abnormal response monitoring in general). Furthermore, we analyzed later error-related components (Pe) as a function of math anxiety. As the bulk of evidence suggests that anxiety does not affect the Pe component, we expected to find no difference in this component between the high and low math anxious individuals for any task. Moreover, given the evidence from numerous anxiety-related studies [18,20,22,26], we expected to find no differences between the groups in terms of response time or error rates for any task. We also used standardized low resolution electromagnetic tomography (sLORETA) [39] to determine the brain electrical sources of the ERN, the CRN and the Pe components, in order to establish whether these error-related components are produced by the same or by slightly different neuroanatomical structures. Finally, differences in voxel activation between tasks in each group were analyzed. We expected that the HMA group would show a greater activation of emotional brain areas when committing an error in a numerical task as compared to an error in a non-numerical task. Obtaining this difference only for the HMA group, but not for the LMA one, might suggest that the fact of failing in a task involving numbers is perceived as an emotional negative event for individuals with high levels of math anxiety, a finding that would contribute to a better understanding of their avoidance of any situation involving the manipulation of numbers.

Methods

Participants

Thirty-four healthy volunteers were tested in this study, half high math anxious and the other half low math-anxious. They were selected from a sample of 452 university students at the University of Barcelona who were assessed for math anxiety, trait anxiety and state anxiety [40,41] (see materials). These tests were administered only in the group formation phase and not during the experimental session.

We initially tested 38 participants but four of them were not included in the analysis: two because of excessive artifacts and the other two because there was no low math-anxious counterpart.

The low math-anxious group (henceforth, LMA) comprised seventeen participants who scored below the first quartile on the Shortened Mathematics Anxiety Rating Scale (sMARS) [40] while the high math-anxious group (henceforth, HMA) comprised seventeen participants who scored above the third quartile on the sMARS.

Groups differed in math anxiety ($t(32) = 19.37$, $p < .001$), but not in trait anxiety ($t(32) = .54$, $p = .59$), state anxiety ($t(32) = 1.42$, $p = .16$), age ($t(32) = .27$, $p = .78$), years of formal education ($t(32) = .74$, $p = .46$), handedness ($\chi^2 = 1.03$, $p = .31$), ethnicity ($\chi^2 = 0.0$, $p = 1$) or gender distribution ($\chi^2 = .18$, $p = .67$). More detailed information about these variables is shown in Table 1.

All participants had normal or corrected-to-normal visual acuity and did not report any history of neurological or psychiatric disorders. All were naïve as to the purposes of the study.

Ethics Statement

Participants were paid for their participation and gave written informed consent before the experiment. The experimental protocol was approved by the Ethical Committee of the University of Barcelona and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Table 1. Means and standard deviations (in brackets) for age, educational level, math anxiety, trait and state anxiety and frequencies for gender and manual dominance for the LMA and the HMA groups.

	Age	Gender	Manual Dominance	Educational level	sMARS	STAI-T	STAI-S
LMA	20.24 (2.07)	13	16	15.59 (1.87)	45.29 (5.19)	19.12 (10.43)	14.18 (8.20)
HMA	20.06 (1.60)	14	17	15.18 (1.28)	84.82 (6.61)	21.06 (10.43)	18.35 (8.90)

Note: LMA: low math-anxious; HMA: high math-anxious; Gender: number of women; Manual Dominance: number of right-handed; Educational level: number of years of formal education. sMARS: shortened Math Anxiety Rating Scale; STAI-T: Trait anxiety subscale from the STAI; STAI-S: State anxiety subscale from the STAI.

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Materials

Groups were formed according to the participants´ scores on the following tests

Shortened Mathematics Anxiety Rating Scale (sMARS). This instrument measures anxiety by presenting 25 situations which may cause math anxiety grouped into three factors: math test anxiety, numerical task anxiety and math course anxiety. *Math test anxiety* (factor I) includes items reflecting apprehension about taking a test in mathematics or about receiving the results. Factor II, labeled *numerical task anxiety*, comprises items reflecting anxiety about executing numerical operations; Factor III, called *math course anxiety*, includes items related with enrolling on and attending a math course and some typical situations. In the present study, we used the Spanish version of the sMARS [40], whose scores have shown strong internal consistency (Cronbach's alpha = .94) and high 7-week test-retest reliability (intra-class correlation coefficient = .72).

State-Trait Anxiety Inventory (STAI). The STAI is a 40-item scale used to measure state (STAI-S) and trait (STAI-T) anxiety. Good to excellent internal consistency (Cronbach´s alpha = .86 - .95) and adequate 30-day test-retest reliability (State: $r = .71$-.76; Trait: $r = .75$-.86) have been reported for the Spanish version of this test [41].

Two tasks were presented to each participant during the recording session: a numerical Stroop task (salient for the HMA group) and a classical Stroop task (control task).

The classical Stroop task. The classical Stroop task was the one proposed by Gehring et al., (2000), in which the words *ROJO* (red), *VERDE* (green) and *AZUL* (blue) were presented in either red or green ink on a computer monitor using a black background. Participants had to respond to the color of the ink in which the word was written, ignoring the color designated by the word. Stroop conditions could be congruent (the ink color matched the semantic meaning of the word, e.g. *ROJO* printed in red ink), incongruent (the color of the ink conflicted with the semantic meaning of the word, e.g. *ROJO* printed in green ink) or neutral (the word did not map directly to either response, e.g. *AZUL* printed in red ink) [18]. The words subtended view angles of 4.01°, 4.98° and 4.01° (horizontally) for *ROJO*, *VERDE* and *AZUL*, respectively, and 0.97° (vertically).

Participants were instructed to press the right or left mouse button in response to the color of the ink in which the word was written. Half of the participants were told to press the left button of the mouse when the color of the ink was red and the right button when the color of the ink was green, and the other half were told to do the opposite. Each trial began with a fixation sign (an asterisk) shown for 500 ms. After a 300 ms pause (a black screen), the word was shown for 200 ms and then followed by a 800 ms-black screen (maximum response windows of 1000 ms). A variable inter-trial interval (600-1100 ms) was used. Following the 24 trials of the training session, the participants received eight blocks of 42 trials (336 total trials).

The numerical Stroop task. In the numerical Stroop task, the stimuli consisted of a pair of Arabic numbers shown simultaneously in the middle of the computer screen. There were four possible types of number pairs: 1-2, 1-8, 2-9, 8-9. Numbers were presented in three sizes: large (font size 80), neutral (font size 60) and small (font size 40). Stimulus pairs subtended view angles of 0.68°, 1.03° and 1.37° (horizontally) and 0.97°, 1.43° and 1.77° (vertically) for large, neutral and small size stimuli, respectively. The participants' task consisted of responding to the number of higher numerical magnitude and ignoring the physical size. Number pairs were presented in three conditions: in the congruent condition, the number of larger numerical magnitude was also larger in physical size (e.g. 8 9), in the incongruent condition, the number of larger numerical magnitude was smaller in physical size (e.g. 8 9) and in the neutral condition the numbers only differed in numerical magnitude, but not in physical size (e.g. 8 9) [38]. Participants were instructed to indicate the number of larger numerical magnitude by pressing the left or right button of the mouse, depending on the side of the screen in which the number of larger magnitude had appeared. For instance, if the number that appeared on the left was larger in magnitude than the one on the right, participants were expected to press the left button of the mouse. The side on which the larger number appeared was counterbalanced, so there were two instances for all number pairs (e.g., 8 9 and 9 8). Each trial began with a fixation sign (an asterisk) shown for 500 ms. After a 300 ms pause (a black screen), a pair of numbers were shown for 300 ms and then followed by a 700 ms-black screen (maximum response windows of 1000 ms). Each trial was followed by a variable inter-trial interval ranging from 600 to 1100 ms. There were 10 blocks of 48 stimuli (480 total trials), preceded by 24 practice stimuli.

Figure 1 shows the sequential presentation of an incongruent stimulus and its timing for the classical (A) and the numerical (B) Stroop tasks. The order of the tasks was counterbalanced, so half of each group participated in the classical Stroop task first and then continued with the numerical task, while the other half did the same in reverse order. Within each task, the trials were randomly presented to each participant.

Both tasks included congruent, incongruent and neutral stimuli in equal proportions and all the stimuli were presented an equal number of times. Participants were asked to answer as fast and as accurately as possible. Moreover, in both tasks, a feedback message was displayed at the end of each block to facilitate error commission. The feedback was based on the participant's performance on the block. If performance was 75% correct or lower, the message *Please try to be more accurate* was displayed; performance above 90% correct was followed by *Please try to respond faster*; otherwise, the message *You are doing a great job* was displayed. The feedback message was followed by a half minute rest.

The E-prime 2.0 program (Psychology Software Tools Inc., Sharpsburg, PA, USA) was used to control the presentation and timing of the stimuli and the measurement of response accuracy and response times.

Procedure. Participants were tested individually. Upon entering the experimental room, they completed standard procedures concerning informed consent along with a demographics questionnaire asking their age, ethnicity, gender and number of years of formal education. Then, EEG/EOG sensor electrodes were attached and the participant was given detailed task instructions. Next, participants were seated 100 cm away from the computer screen in an electrically-shielded, sound-attenuating recording chamber. For each task, the experimental session began with a training period of 24 trials. When participants achieved 65% of hits in the training period, the recording session started. The training trials were only used to familiarize the participants with the task, so they were excluded from the statistical analysis. The experiment, including electrode placement and execution of the practice and test phases, lasted about 120 min.

Electrophysiological recording

The EEG was recorded with ANT hardware and software (B.V., Enschede, The Netherlands) from 64 electrodes positioned according to the extended 10/20 system, as well as two electrodes on the right and left mastoids, and mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH. ANT Advanced Neuro Technology). EEG channels were continuously digitized at a rate of 512 Hz by an ANT amplifier (B.V., Enschede, The Netherlands). A band-pass filter was set from 1.6 to 30 Hz, and electrode impedance was kept below 5 kΩ. The horizontal and vertical electrooculogram was recorded with electrodes placed at the outer canthus and below the right eye respectively. The common reference electrode was placed on the tip of the nose and ground was located at AFz. For figures, grand average waveforms were low-pass filtered at 15 Hz.

Source localization

Source localization was carried out using standardized low-resolution brain electromagnetic tomography (sLORETA) [39] to identify the brain areas generating the ERN, CRN and Pe

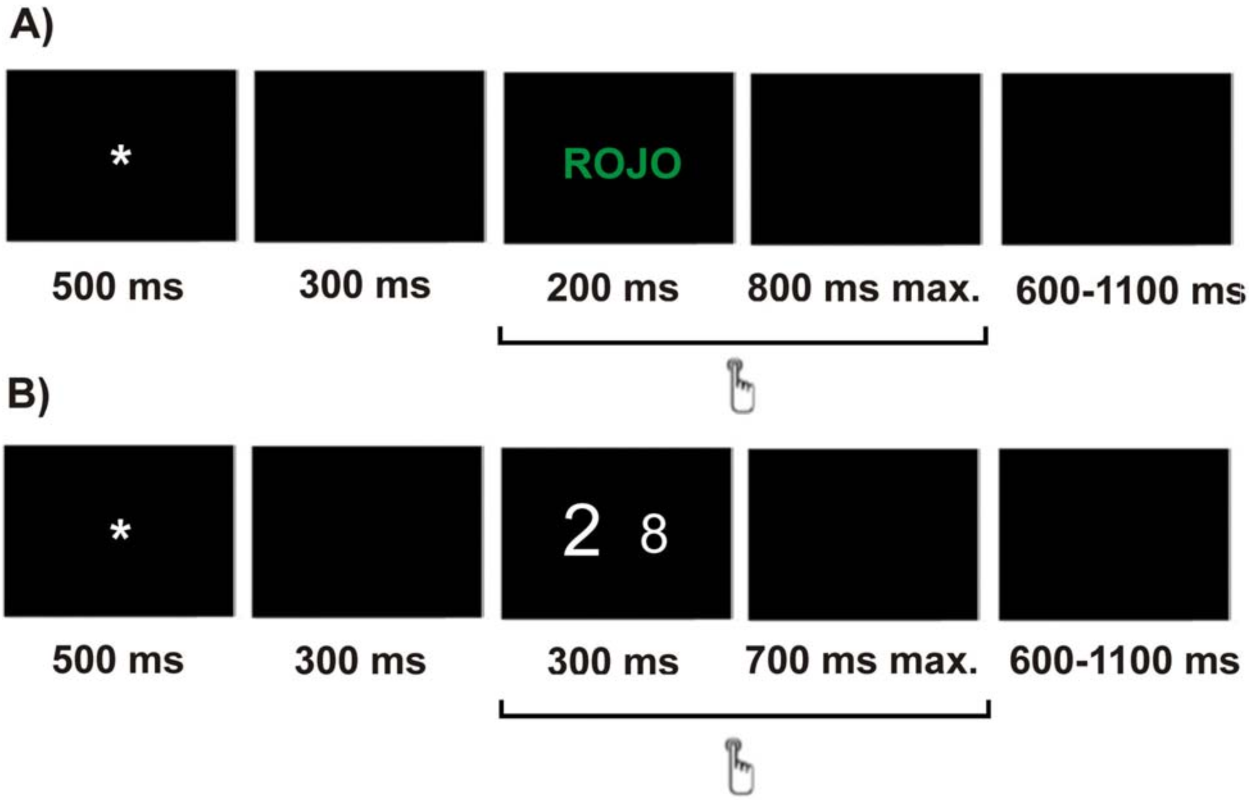

Figure 1. One trial structure of an incongruent stimulus of the classical (A) and numerical (B) Stroop tasks and its timing.

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components. The brain activity of the two groups in each task and between the tasks in each group was also compared for the three components. sLORETA estimates the sources of activation on the basis of the standardized current density at each of 6239 voxels in the gray matter and the hippocampus of the MNI-reference brain with a spatial resolution of 5 mm. The calculation is based upon a linear weighted sum of the scalp electrical potentials, with the assumption that neighboring voxels have maximal similar electrical activity. sLORETA solutions are computed within a three-shell spherical model co-registered with the MNI152 digitized structural human brain atlas template [42]. Therefore, these solutions are given in three coordinates: *X* is the distance in millimeters to the right (+) or left (-) of midline, *y* is the distance anterior (+) or posterior (-) to the anterior commissure, and *z* is the distance above (+) or below (-) a horizontal plane through the anterior and posterior commissures.

Under ideal conditions, solutions provided by sLORETA, which are based on distributed brain activity, have no localization bias and achieve reliable localization of possible underlying sources [43,44].

Data Analysis

Behavioral data

Medians of response time were calculated for each participant in each task. The response time (RT) for error and correct responses and the percentage of error responses were analyzed through analyses of variances (ANOVAs).

Firstly, an ANOVA was performed to analyze reaction time taking *Response type* (error and correct) and *Task* (numerical and classical) as within-subject factors and *Group* (LMA and HMA) as the between-subjects factor.

Regarding the percentage of errors, an ANOVA was performed taking *Task* as within-subject factor and *Group* as the between subjects factor.

In addition to reaction times and accuracy, we examined participants' post-error measures. For post-error slowing we analyzed the median of reaction times following errors and following correct responses and carried out an ANOVA taking Previous *response type* (error and correct) and *Task* (numerical and classical) as within-subject factors and *Group* (LMA and HMA) as the between-subjects factor. Regarding post-error accuracy, we calculated the percentage of errors that followed error responses and the percentage of errors that followed correct responses. We carried out an ANOVA, taking

Previous *response type* and *Task* as within-subject factors and *Group* as the between subjects factor.

The *F* value, the uncorrected degrees of freedom, the probability level following correction, the ε value (when appropriate) and the η^2 effect size index are given in the results section.

Error-related potentials

ERPs were averaged for each participant time-locked to the response onset, including error responses (for the ERN) and correct responses (for the CRN) for all experimental conditions. The averaged EEG epochs were rereferenced to the mastoids' mean activity. The average was constructed from -400 to 600 ms epochs relative to the response onset. A 100-ms window prior to the response (-200 to -100 ms) served as the baseline. Trials with voltages exceeding ± 100 µV in any electrode were excluded from the ERP average. Ocular artifacts were identified and corrected with the eye-movement correction algorithm used in the EEprobe program (ANT, The Netherlands). Previous evidence suggests that the ERN component stabilizes using a minimum of six to eight error trials [45]. In our study, all participants had at least eight error trials in each task. Despite the ERN is typically quantified in the 0-100 ms window (e.g. [21]), in our study, both the ERN and the CRN components were quantified as a mean amplitude measure in the 50-90 ms window following a correct response (CRN) or an error response (ERN), given that this was the window where differences between groups were shown maximal.

A repeated measures ANOVA was performed on the ERP mean amplitude at Fz, taking *Response type* and *Task* as the within-subject factors and *Group* as the between-subjects factor. Another repeated measures ANOVA was performed on the ERP difference in amplitude (ERN-CRN) at Fz taking *Task* as the within-subject factor and *Group* as the between-subjects factor.

Regarding the Pe component, we carried out a repeated measures ANOVA on the ERP mean amplitude in the 150-250 ms window at Cz, taking *Response type* and *Task* as within-subject factors and *Group* as the between-subjects factor. We performed tests of simple effects whenever an interaction was significant and used the Bonferroni correction to control for the increase in type I error.

Source analysis

The voxel-based sLORETA-images were calculated for each group in each task and were also compared between the two groups (LMA vs. HMA) and between the two tasks (classical and numerical) using the sLORETA-built-in voxelwise randomization tests (5000 permutations), based on statistical non-parametric mapping (SnPM; for details see 43). The differences in localization between groups and tasks were computed by a voxel-by-voxel *t*-test for independent measures of the average sLORETA-images over the 50-90 ms window for the ERN and CRN and over the 150-250 ms window for the Pe component. The statistical sLORETA analysis gives the exact significance thresholds, regardless of non-normality and corrected for multiple comparisons. The significant differences between conditions at respective MNI coordinates and Brodmann areas (BA) are reported in the results section.

Table 2. Means (of medians) and standard errors (in brackets) for behavioral and ERP measures.

	Classical Stroop Task		**Numerical Stroop Task**	
	LMA	**HMA**	**LMA**	**HMA**
Response time (ms)				
Error trials	251.88 (8.49)	256.29 (12.74)	305.76 (6.62)	315.35 (7.85)
Correct trials	309.76 (7.55)	308.59 (7.60)	339.88 (8.55)	360.88 (10.35)
Accuracy				
No. of error trials	32.94 (4.18)	30.06 (4.00)	59.65 (7.03)	54.00 (5.78)
No. of correct trials	288.24 (8.17)	301.00 (5.18)	420.35 (7.03)	426.00 (5.78)
% of error trials	10.24 (1.23)	8.99 (1.17)	12.42 (1.46)	11.25 (1.20)
ERPs (µV)				
ERN	-3.99 (.57)	-3.76 (.90)	-4.19 (.71)	-6.38 (.67)
CRN	1.68 (.81)	2.27 (.67)	-.79 (.61)	.13 (.44)
ERN-CRN	-5.67 (.92)	-6.03 (.77)	-3.39 (.52)	-5.67 (.92)
Pe on error trials	2.94 (.87)	1.69 (.84)	2.05 (.69)	.74 (.59)
Pe on correct trials	1.13 (.40)	.53 (.59)	1.41 (.39)	1.21 (.46)

Note: Voltage for ERN and CRN in Fz for the 50-90 ms time window; Voltage for Pe in Cz for the 150-250 ms time window.

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Results

Behavioral Data

Regarding reaction time, responses were faster on error trials (mean = 282.32, SEM = 5.41) than on correct trials (mean = 329.77, SEM = 5.29) (F(1,32) = 95.94, p < .001, η^2 = .75) and were slower on the numerical Stroop task (mean = 330.47, SEM = 5.58) compared with the classical Stroop one (mean = 281.63, SEM = 5.50) (F(1,32) = 75.20, p < .001, η^2 = .70). Moreover, the *Response type x Task* interaction was also significant (F(1,32) = 4.73, p = .03, η^2 = .12), showing greater differences between tasks when the participants committed an error (classical: mean = 254.08, SEM = 7.65; numerical: mean = 310.55, SEM = 5.13) than when they gave a correct response (classical: mean = 309.17, SEM = 5.35; numerical: mean = 350.38, SEM = 6.71) (p < .001). No group main effect or interaction reached statistical significance (all p values ≥ .23).

Concerning accuracy, more errors were committed on the numerical Stroop task (mean = 11.83, SEM = .94) than on the classical one (mean = 9.61, SEM = .85) (F(1,32) = 6.39, p = .01, η^2 = .16). No group main effect or interaction reached statistical significance (all p values ≥ .44). Accuracy and response time means and standard deviations are shown in Table 2.

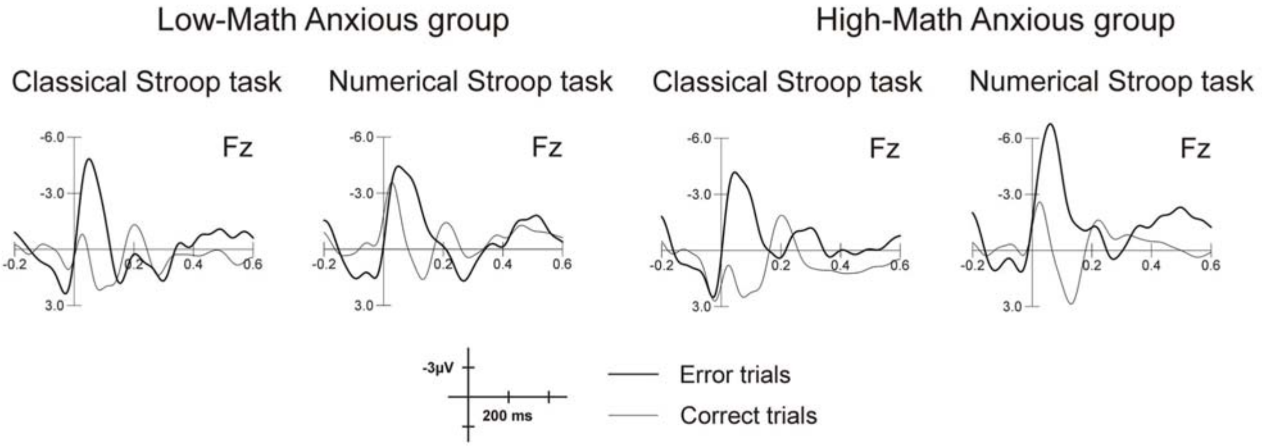

Figure 2. Raw grand average waves for correct and error trials for LMA and HMA groups in the classical and the numerical Stroop tasks at Fz.

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Post-error measures. We found a significant main effect of *Previous response type* (*F*(1,32) = 38.36, *p* < .001, η^2 = .54), showing that participants were slower after committing an error (mean = 346.70, SEM = 7.27) than after correct responses (mean = 324.50, SEM = 5.41). We found a significant Task x Previous *response type* interaction (*F*(1,32) = 10.16, *p* = .003, η^2 = .24). This interaction was due to a difference between previous response types in each task, being greater for the classical task (RT after correct responses: mean = 303.38, SEM = 5.59; RT after error responses: mean = 335.00, SEM = 9.55) than for the numerical task (RT after correct responses: mean = 345.61, SEM = 6.74; RT after error responses: mean = 358.41, SEM = 7.49). No group effect or interaction reached statistical significance (all *p* values ≥ .13).

Finally, with respect to post-error accuracy, the overall ANOVA showed a significant main effect of *Previous response type* (*F*(1,32) = 1720.55, *p* < .001, η^2 = .98), showing that there was a lower percentage of errors after errors (mean = 11.27, SEM = .93) than after correct responses (mean = 88.72, SEM = .93). All the other main effects and interactions were non-significant (all p values ≥ .11).

Event-related potentials

Error-related negativity (ERN) ***and*** **Correct-related negativity (CRN).** Amplitude was more negative for error trials (mean = -4.58, SEM = .42) than for correct trials (mean = .82, SEM = .43) (*F*(1,32) = 157.41, *p < .001,* η^2 = .83). Figure 2 shows this early negativity for error commission as compared to correct responses in both the classical and the numerical Stroop tasks for the LMA and HMA groups at Fz. The mean amplitudes for the ERN and the CRN in the 50-90 ms windows are shown in Table 2.

Moreover, the amplitude was more negative in the numerical (mean = -2.80, SEM = .37) than in the classical (mean = -.94, SEM = .43) Stroop task (*F*(1,32) = 30.48, *p* < .001*,* η^2 = .48).

The Response type x Group interaction was also significant (*F*(1,32) = 2.07, *p* = .05*,* η^2 = .11), showing that, despite the fact that the two response types differed significantly in each group (*p* < .001), the HMA group showed a greater voltage difference between an error (mean = -5.07, SEM = .60) and a correct (mean = 1.20, SEM = .61) response than the LMA (error: mean = -.40, SEM = .60; correct: mean = .44, SEM = .61) one. Finally, the global ANOVA showed a significant *Group x Task x Response type* interaction (*F*(1,32) = 4.89, *p* = .03*,* η^2 = .13). No other main effect or interaction reached statistical significance (all p values ≥ .13)

In order to analyze this *Group x Task x Response type* interaction further and to probe our hypothesis, we carried out a separate ANOVA for each group, comparing participants' ERN in each task. While no significant effect of *Task* was shown for the LMA group (*F*(1,16) = .10, *p* = .75*,* η^2 = .006), this effect emerged for the HMA one (*F*(1,16) = 7.44, *p* = .01*,* η^2 = .31), the ERN being more negative for the numerical (mean = -6.38, SEM = .67) as compared to the classical (mean = -3.76, SEM = .90) Stroop task. Grand average waveforms elicited by errors for each group in each task at Fz are shown in Figure 3A. This figure shows a greater amplitude of the ERN for the HMA group when solving the numerical task as compared to the control task, while no difference between tasks can be appreciated for the LMA group. This difference is more evident in Figure 3B, where topographic maps for numerical and classical Stroop tasks are shown for both groups in the 50-90 ms window. Topographic maps were plotted using the EEProbe 3.1 program (ANT Software BV, Enschede, The Netherlands).

ERP difference wave (ERN-CRN). The analysis of the difference wave showed a significant *Task x Group* interaction (*F*(1,32) = 4.90, *p* = .03*,* η^2 = .13), showing that groups differ only on the numerical task (*F*(1,32) = 12.02, *p* = .002*,* η^2 = .27) but not on the classical (*F*(1,32) = .08, *p* = .76, η^2 = .003) task. The main effect of group also reached significance (*F*(1,32) = 4.08, *p* = .05, η^2 = .11), while the main effect of *Task* did not (*F*(1,32) = 2.06, *p* = .16, η^2 = .06).

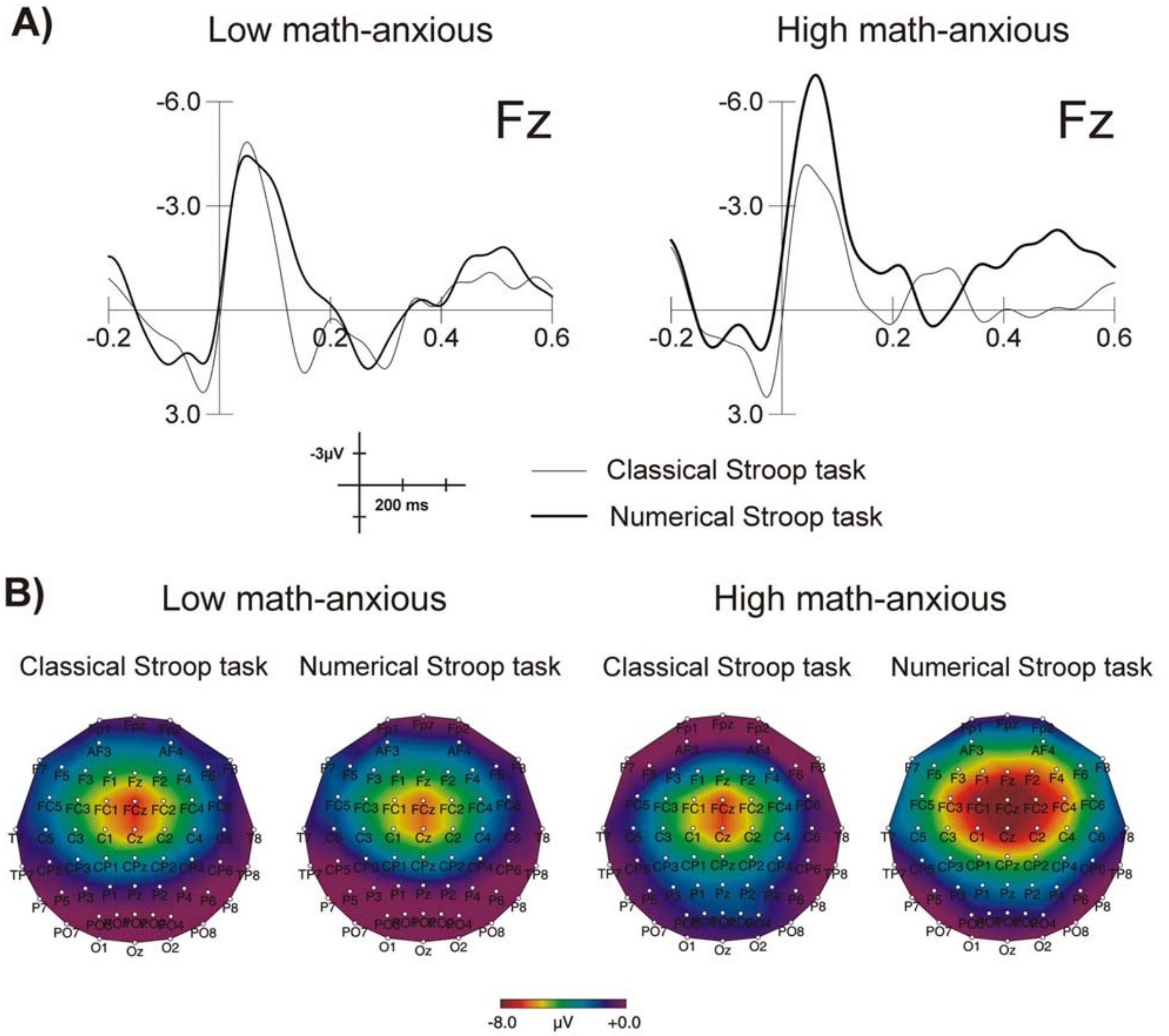

Figure 3. Image of error-related brain potentials. Grand average waveforms for the ERN at Fz for the LMA and the HMA groups in the numerical and the classical Stroop tasks (A) and scalp topography of the ERN component in the 50-90 ms window after the commission of an error for the LMA and the HMA groups in the classical and numerical Stroop tasks (B).

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Error-related positivity (Pe). Figure 4A shows grand average waveforms for the Pe component elicited by error and correct responses for each group in each task at Cz. The overall ANOVA showed a significant *Task x Response type* interaction ($F(1,32) = 8.76$, $p = .006$, $\eta^2 = .21$) showing that the response types differed only for the classical Stroop task ($t(33) = 2.72$, $p = .01$) but not for the numerical ($t(33) = .22$, $p = .82$); the amplitude was greater for an error (mean = 2.31, SEM = .60) than for a correct (mean = .83, SEM = .35) response. Besides the *Response type* main effect, which was marginally significant, all the *Group* main effect and interactions were far from significant (all p values ≥ .30). Table 2 also shows the mean amplitude for the Pe component in error and correct trials at Cz for the 150-250 ms window for both groups in the two tasks. Figure 4B shows the topographic maps for the Pe after errors in the numerical and the classical Stroop tasks for both groups in the 150-250 ms window. This figure shows that the Pe component after the commission of a numerical error seems to be reduced compared to the other conditions.

Correlational analysis

We correlated participants' scores on the sMARS test and in its three subscales with the mean electrophysiological activity for the ERN and CRN in the 50-90 ms window and for the Pe

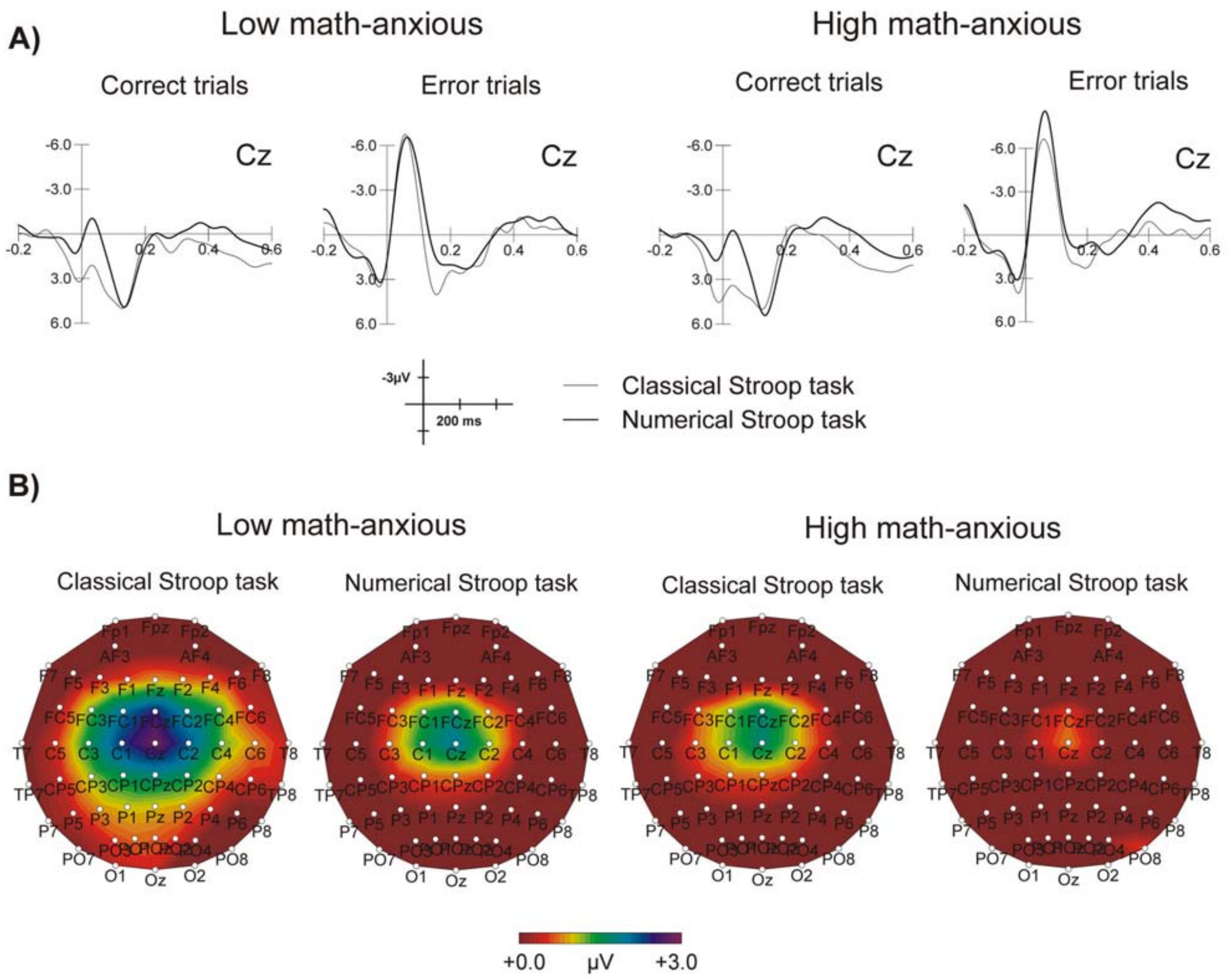

Figure 4. Image of error-related brain potentials. Grand average waveforms at Cz for the Pe component after errors and correct responses for the LMA and the HMA groups in the numerical and the classical Stroop tasks (A) and scalp topography of the Pe component after errors in the 150-250 ms window for the LMA and the HMA groups in the classical and numerical Stroop tasks (B).
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component in the 150-250 ms window for both tasks for the whole sample (n = 34). Pearson correlation coefficients and *p*-values are reported in Table 3. This table shows that as self-reported measures of math anxiety increased, the ERN for the numerical task became more negative. Nevertheless, this effect was absent for the classical task and for the CRN and Pe components in the numerical task. Moreover, it is worth mentioning that while the ERN-CRN difference wave correlated with the three subscales of the sMARS, the raw ERN wave correlated only with the Factor I subscale of this test, that is, with math test anxiety.

Source localization

For the ERN. Table 4 shows Brodmann areas of statistically stronger cerebral activation ($p < .01$) for the ERN (in red) for the LMA and the HMA groups in the classical and numerical Stroop tasks. This table shows that, as suggested by numerous studies, the ERN in all tasks and in the two groups implied, mainly, the activation of the Anterior cingulate cortex, the cingulate gyrus (both frontal and limbic), and the medial and middle frontal gyrus.

Very interestingly, sLORETA analysis showed that the HMA group activated different brain areas when committing an error on the numerical task compared with the classical task, and compared with the LMA group on any task. For example, the HMA group showed significant activation of the occipital cuneus, the superior parietal lobule, the transverse temporal gyrus and the supramarginal parietal gyrus. Moreover, within the brain structures that also showed activation for the other conditions, more Brodmann areas were activated in the case of errors committed by HMA individuals in the numerical task, for example, at the Anterior cingulate cortex (BA 10 and 25),

Table 3. Pearson correlation coefficients (*p* values under brackets) between the sMARS scores and ERN, CRN and ERN-CRN components (at Fz) and Pe component (at Cz) amplitudes for the numerical and the classical Stroop tasks for the whole sample (n=34).

	Classical Stroop task				**Numerical Stroop task**			
	ERN	**CRN**	**ERN-CRN**	**Pe**	**ERN**	**CRN**	**ERN-CRN**	**Pe**
sMARS	.02 (.89)	-.09 (.60)	-.06 (.73)	-.15 (.37)	-.35 (.03)*	.17 (.32)	-.48 (.003)**	-.22 (.19)
Factor I	.02 (.87)	-.07 (.67)	-.04 (.81)	-.17 (.32)	-.38 (.02)*	.16 (.35)	-.50 (.002)**	-.22 (.19)
Factor II	.05 (.74)	-.13 (.43)	-.07 (.69)	-.07 (.67)	-.26 (.13)	.11 (.53)	-.34 (.04)*	-.20 (.24)
Factor III	-.01 (.94)	-.05 (.74)	-.06 (.72)	-.10 (.56)	-.19 (.25)	.19 (.26)	-.34 (.04)*	-.13 (.43)
STAI-T	.12 (.48)	.16 (.35)	-.03 (.85)	-.17 (.32)	-.01 (.91)	.14 (.41)	-.12 (.47)	-.30 (.07)
STAI-S	.14 (.39)	.09 (.60)	.05 (.77)	-.03 (.86)	-.04 (.81)	-.03 (.85)	-.01 (.92)	-.24 (.15)

Note. ** *p* < .01; * *p* < .05; Factor I: Math test anxiety; Factor II: Numerical task anxiety; Factor III: Math course anxiety; ERN: Error-related negativity; CRN: Correct-related negativity; Pe: error positivity (after errors).

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Table 4. Brodmann areas of statistically stronger cerebral activation

Lobe	**Structure**	**Classical**		**Numerical**	
		LMA	**HMA**	**LMA**	**HMA**
Limbic	Anterior Cingulate	**24, 32,** 33 / 32 / 24, 32, 33	**24, 32,** 33 / 24, 32	**24, 32,** 33 / 24	**10, 24, 25,** 32 / 24, 32
Frontal	Cingulate Gyrus	32 / 32	**32**	32 / 32	**6,** 32 / 32
Limbic	Cingulate Gyrus	**23, 24, 31,** 32 / 23 / 24, 31, 32	**24,** 32 / 24, 31, 32	**23, 24, 31,** 32 / 23, *24,* 31/ 24, 31, 32	**23, 24, 31,** 32 / 23, *24, 31*
Occipital	Cuneus	-	-	-	**30**
Sub-Lobar	Extra-Nuclear	*47*	*47*	*47*	*47*
Temporal	Fusiform Gyrus	*20, 36, 37*	*20, 36, 37*	20 / 20, *36, 37*	*20, 36, 37*
Occipital	Fusiform Gyrus	-	*37*	*37*	*37*
Frontal	Inferior Frontal Gyrus	**6,** 9 / 13, *45, 47*	*13, 45, 46, 47*	9 / 45, *47*	**6, 9, 11,** 44 / 45, *47*
Parietal	Inferior Parietal Lobule	40 / 40	*40*	40 / 40 / 40	40 / 40
Limbic	Inferior Temporal Gyrus	*20*	*20*	*20*	20 / 20
Temporal	Inferior Temporal Gyrus	*37*	-	*37*	*37*
Sub-lobar	Insula	13 / 13, *45*	*13, 45*	13 / 13, *45*	13 / 13, *45*
Temporal	Insula	*41*	*41*	41 / 41	41 / 41
Occipital	Lingual Gyrus	-	-	*19*	**18,** 19 / 19
Frontal	Medial Frontal Gyrus	**6,** 32 / 9, *10, 11* / 6, 8, 9	**6, 8, 9, 10,** 11 / 6, 9, 32	**9,** 32 / 6 / 6	**6, 8 , 9 , 10 , 11 ,** 32 / 6 / 6, 9
Frontal	Middle Frontal Gyrus	6 / 10, 46 / 6	**10,** 11 / 10, 46 / 6		**6, 9, 10,** 46 / 6
Temporal	Middle Temporal Gyrus	*21, 38*	*21, 38*	22 / 21, *22, 37, 38, 39*	**20, 21, 22, 39** / *21, 22, 37, 38, 39*
Frontal	Orbital Gyrus	-	**11**	*47*	11 / 47
Frontal	Paracentral Lobule	**6,** 31 / 5	31	31 / 5	**5, 6,** 31 / 31
Limbic	Parahippocampal Gyrus	-	*19, 27, 28, 36, 37*	19 / 19, *27, 28, 30, 34, 35, 36, 37*	**19, 27, 28, 30, 34, 35,** 36 / 19, *27, 28, 30, 34, 35, 36, 37*
Frontal	Postcentral Gyrus	-	-	3 / 3	**3,** 4 / 3
Parietal	Postcentral Gyrus	*2,* 40 / 5	*2, 40, 43*	**2, 3,** 40 / 2, *3,* 40 / 2, 3, 40	**1, 2, 3, 5, 40,** 43 / 2, *3, 40*
Limbic	Posterior Cingulate	**23**	-	*23, 29, 30*	**23, 29, 30,** 31 / 23, *29, 30*

inferior frontal gyrus (11 and 44), middle frontal gyrus (9 and 46), parietal post-central gyrus (1,5,43) or parahippocampal gyrus (27,28,30,34–36). Finally, voxel activation for the HMA group on the numerical task also involved areas that, for the LMA group (and the HMA in the classical task) were mainly active for correct responses (CRN), such as the inferior temporal gyrus (limbic), the middle temporal gyrus, the posterior cingulate, the limbic sub gyral or the parahippocampal gyrus (limbic). The involvement of greater voxel activation can be seen in Figure 5A, where cortical areas that showed significant activation ($p < .01$) for the ERN component (50-90 ms) for each group in each task are shown in red-to-yellow colors (*t*-values).

Despite the apparent activation of a greater number of voxels for the numerical errors in the HMA group, the statistical comparison between groups did not show significant results, either for the classical ($t = 4.82$, $p = .67$) nor for the numerical ($t = 4.79$, $p = .69$) Stroop task.

Nevertheless, significant differences emerged when comparing tasks in each group. The results showed that while no differences were found for the LMA group ($t = 4.89$, $p = .56$), the HMA group showed a significant ($t = 4.76$, $p = .04$) difference in activation between tasks. Those differences were located at the insula, which showed a greater activation for the numerical task (max *t* value = 6.61) than for the classical task (max *t* value = 2.52). Table 5 shows the Brodmann areas, MNI coordinates and t values for the voxels presenting significant differences between tasks for the HMA group. Figure 5B shows, in red-to-yellow colors, cortical areas with significant ($p < .05$) differences between tasks for the LMA and the HMA groups, showing the greater difference between tasks for the

Table 4 (continued).

Lobe	Structure	Classical		Numerical	
		LMA	HMA	LMA	HMA
Frontal	Precentral Gyrus	**6**	4	**4,** 6 / 4, 6	**4, 6, 43**
Frontal	Precuneus	-	-	31/ 31/ 31	31 / 31
Parietal	Precuneus	7 / 7	-	*7,* 31/ 7	**7,** 31 / 7*, 31*
Frontal	Rectal Gyrus	-	11 / 11	*11*	11/ 11
Frontal	Subcallosal Gyrus	-	-	*34*	*34*
Frontal	Sub-Gyral	6 / 10	6	-	**6, 8**
Limbic	Sub-Gyral	-	-	*19, 31*	31 / 19*, 31*
Parietal	Sub-Gyral	**2**	-	2 / 2, 40 / 2, 40	**2,** 40 / 2*, 40*
Temporal	Sub-Gyral	*37*	*21*	*13, 20, 21, 37*	*13, 20, 21, 37*
Frontal	Superior Frontal Gyrus	6 / 10, *11*	**8, 10,** 11 / 6	**6**	**6, 8, 10, 11**
Parietal	Superior Parietal Lobule	-	-	5	**7**
Temporal	Superior Temporal Gyrus	*13, 22, 38, 41*	*13, 22, 38, 41, 42*	**13,** 41 / 13*, 22, 38, 41*	**13, 21, 22, 39, 41, 42** / *13, 22, 38, 41*
Parietal	Supramarginal Gyrus	-	-	-	40 / 40
Temporal	Transverse Temporal Gyrus	-	-	-	**41, 42**
Limbic	Uncus	*20, 28, 36, 38*	*20, 28, 36, 38*	*20, 34, 36, 38*	*20, 34, 36, 38*

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HMA group. More concretely, when analyzing the HMA group's brain activity in each task, a greater insular activation was found for the numerical (6.61) as compared to the classical (2.52) Stroop task at the right insula.

For the CRN. Table 4 shows Brodmann areas with statistically stronger cerebral activation (*p* < .01) for the CRN (in blue) for the LMA and the HMA groups in the classical and the numerical Stroop tasks. This table shows that the CRN activated some areas previously found to activate the ERN, such as the cingulate gyrus (limbic lobe), inferior parietal lobule, the insula or the precuneus. Moreover, in other cases the CRN activated the same brain structures as the ERN, but different Brodmann areas were involved in the generation of each component. For example, in the case of the inferior frontal gyrus, while the activation of the ERN was located at Brodmann areas 6, 9, 11 and 44, the CRN activated different areas (13,45–47). Despite the overlapping of some areas in the generation of the ERN and the CRN, the CRN also showed a specific activation of certain brain regions such as the uncus, the temporal sub gyral, the extra-nuclear (sub lobar), the temporal and occipital fusiform gyrus or the inferior temporal gyrus (limbic and temporal). Very interestingly, the CRN showed no voxel activation at the anterior cingulated.

The comparison between tasks did not reach significance either for the LMA group (*t* = 4.73, *p* = .44) or for the HMA group (*t* = 4.76, *p* = .29). Similarly, groups showed non-significant differences both for the classical (*t* = 4.64, *p* = .98) and for the numerical (*t* = 4.71, *p* = .86) tasks.

For the ERN vs CRN. Figure 6 presents, in red to yellow colors (*t* values), the cortical areas that showed significant activation (*p* < .01) for the ERN as compared to the CRN, for the two tasks in the two groups. As expected, for all conditions, this differential activity was shown mainly in the Anterior cingulate cortex (Brodmann areas 24, 32, 33) and in the cingulated gyrus (Brodmann areas 24 and 33). Nevertheless, for the HMA group in the numerical condition, there was an area that showed even a greater activation, the insula (Brodmann area 13).

For the Pe component. Table 4 shows Brodmann areas with statistically stronger cerebral activation (*p* < .01) for the Pe component (in green) for the LMA and the HMA groups in the classical and the numerical Stroop tasks. Like the ERN, the Pe showed significant voxel activation at the Anterior cingulate cortex, the frontal cingulate gyrus, the precuneus, the limbic cingulate gyrus (except for HMA in the numerical task), frontal paracentral lobule and the middle and medial frontal gyrus. Nevertheless, in contrast to the CRN, which showed activation of different areas with respect to ERN, the Pe component showed no activation of different brain structures, that is, all the activated brain areas also showed activation for the ERN.

As in the case of the CRN, the comparison between tasks showed no statistical differences for the LMA (*t* = 4.78, *p* = .18) and the HMA (*t* = 4.60, *p* = .78) group. Neither did the differences between groups reach significance for the classical (*t* = 4.66, *p* = .42) or numerical (*t* = 4.64, *p* = .84) tasks.

Discussion

This study aimed to investigate error monitoring processing in individuals high in math anxiety in order to improve our understanding of the difficulties experienced by individuals with high math anxiety when they have to manipulate numbers. To the best of our knowledge, this is the first time that error monitoring processes have been explored in a cohort of this kind. To do so, we formed two groups that presented extreme scores of math anxiety, but did not differ in trait or state anxiety. This adds value to the study, as it enables us to rule out the possibility that any differences between the groups were due to general anxiety. Both groups had to solve a numerical Stroop task (more salient for the HMA group) and a classical Stroop task (control task). We used ERPs to analyze the electrophysiological response after errors and after correct responses. We expected to find differences between tasks only for the HMA group.

Our results confirmed our hypotheses. Consistent with studies of other anxiety disorders [18,20,22–24], non-clinical individuals with a high level of math anxiety were characterized by increased error-related brain activity and by a greater difference between the ERN and the CRN when they solved a numerical task, but not when they solved a task involving non-numerical stimuli. The specificity of these results for the ERN but not for the CRN suggests that HMA individuals differ from their LMA counterparts not in generic response monitoring processes, but specifically in the evaluation of errors [18,31].

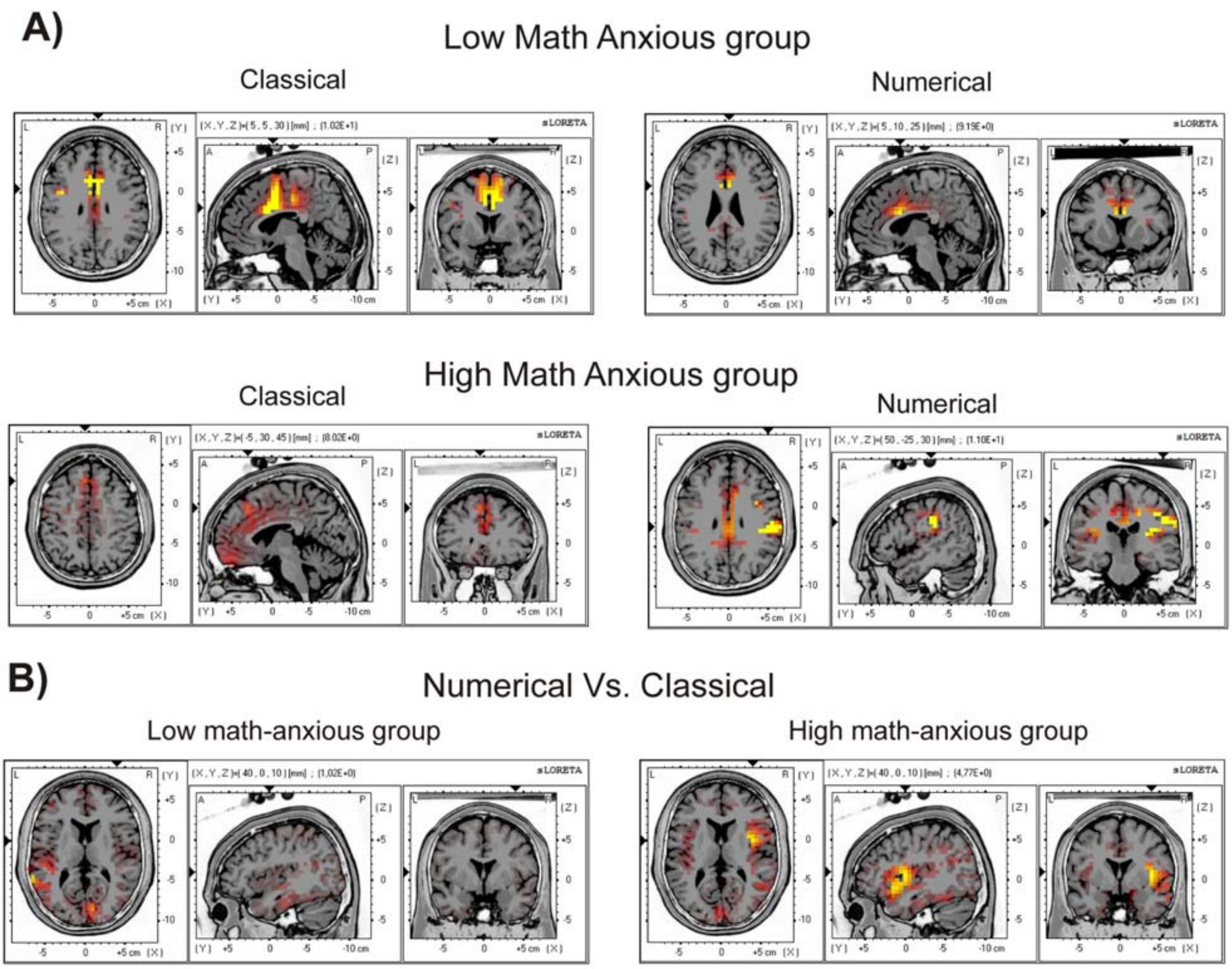

Figure 5. Images of neural activity computed with sLORETA. The images represent cortical areas showing significant activation ($p < .01$) for the ERN (50-90 ms window) for the LMA and the HMA group in the numerical and the classical Stroop task (A) and areas showing significant differences ($p < .05$) between the classical and the numerical Stroop tasks for the LMA and the HMA groups (B).

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With respect to the Pe component, neither the group main effect nor the interactions reached statistical significance, which corroborates the results of previous studies claiming that individual differences in anxiety do not seem to modulate later and more elaborate stages of error monitoring [19,21,35,46]. Nevertheless, we found a significant difference between response types, with the Pe component being more positive after errors than after correct responses (see 46,47 for similar results). However, this effect was only found for the classical Stroop task, while in the numerical task both errors and correct responses generated a very similar Pe component. This might be due to a reduction of the Pe component for the numerical errors in the HMA group (shown clearly in Figure 4B). In this respect, despite differences between groups were non-significant, this tendency of the HMA group to show smaller Pe amplitudes after errors has also been found previously [18,20].

Table 5. Areas of statistically higher localized brain activation for the numerical task compared with the classical task for the HMA group.

Lobe	Structure	B.A.	MNI coordinates (x,y,z)	*T*-value
Sub Lobar	Insula	13	40, 0, 5	4.83
Sub Lobar	Insula	13	40, 0, 10	4.77

Note: B.A: Brodmann Area; MNI: Montreal Neurological Institute; *t*-value of the statistical comparison with $p < .05$ for *t*-values above 4.76 (threshold).

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Given that the Pe component is considered to show conscious error processing, this finding could be suggesting that HMA individuals might not be fully conscious about having

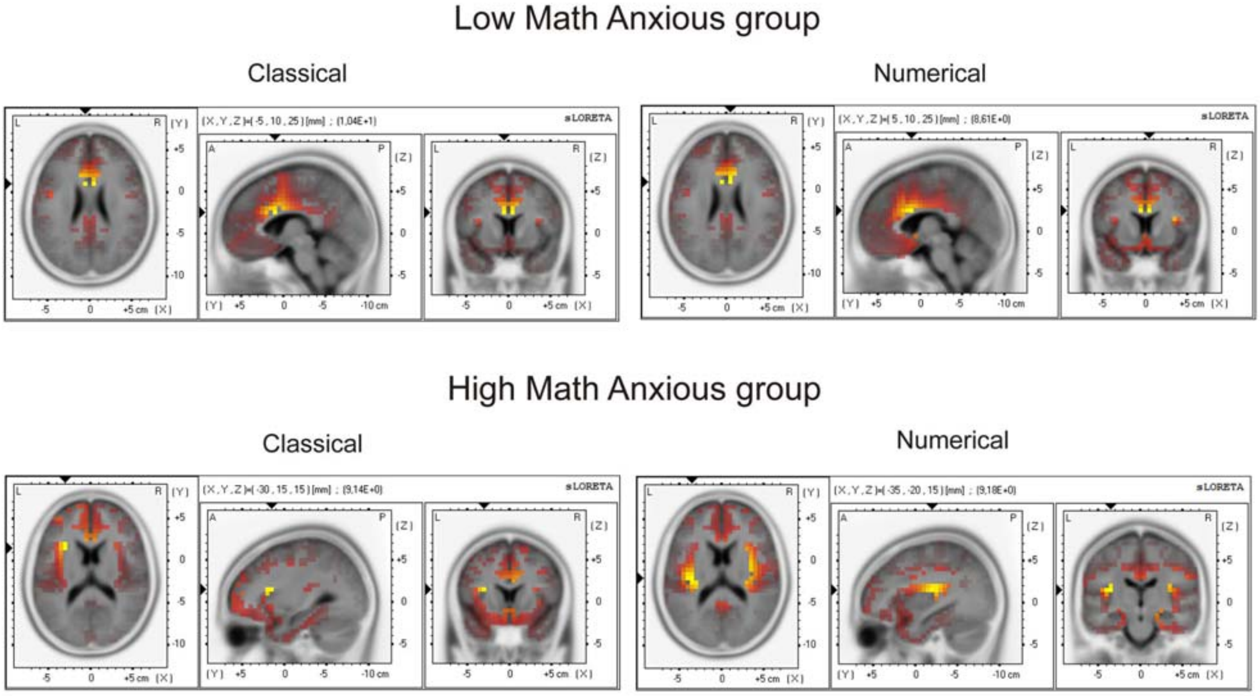

Figure 6. Images of neural activity computed with sLORETA. The images represent cortical areas showing significant activation (p < .01) for the ERN as compared to the CRN in the 50-90 ms window for the LMA and the HMA groups in the numerical and the classical Stroop tasks.

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committed a numerical error, as compared to an error in the non-numerical task. The relationship between the Pe component and math anxiety deserve further research, especially because of the great consequences that this possible lack of error consciousness could have in the process of mathematical learning. Regarding source localization analysis, the ERN activity mainly involved the Anterior cingulate cortex (Brodmann areas 24, 32 and 33) [9,11], and the medial and middle frontal gyrus (Brodmann area 6) [36], corresponding to the Supplemental motor area (SMA) (adjacent to the caudal part of the Anterior cingulate cortex) which has also been suggested to be a generator of the ERN [48]. The activation as well of some voxels at the insula, precuneus or posterior cingulate areas suggests a distributed error processing in the human system (see also 49). As for the CRN, it did not activate anterior cingulated brain areas. Hence, our results corroborate previous evidence suggesting that the CRN and the ERN involve different neural generators, with a greater involvement of posterior cingulate areas for the CRN and of anterior cingulated areas for the ERN [31]. The Pe showed activation mainly of the Anterior cingulate cortex (Brodmann area 24) and cingulate gyrus [36] and voxel activation seemed to be restricted to those areas that showed activation for the ERN, suggesting that these components were generated by the same ACC regions (see also 50,51).

Moreover, across both groups, greater levels of math anxiety were associated with larger ERN only on the numerical task. A negative correlation between the level of anxiety and the amplitude of ERN has also been obtained in studies exploring GAD patients [21]. Interestingly, despite the fact that the ERN-CRN difference wave correlated with the three subscales of the sMARS, for the ERN raw wave the correlation only held for the Factor I subscale, that is, for math test anxiety. This could be suggesting that it is the evaluative aspect of math anxiety (math test anxiety) that best explains the relationship between math anxiety and error monitoring in our sample. In fact, previous studies have found that the presence of overt performance evaluation led to increased ERN responses compared to a non-evaluation condition [52].

Despite the differences found in electrophysiological measures, the groups did not differ in reaction time and percentage of errors [18,20,22–24,53]. This suggests that the exaggerated processing of errors in the HMA group (enhanced ERN) did not lead to increased behavioral regulation, which might imply an inefficient action monitoring. Regarding post-error measures, we found the classical slow-down in reaction time and increase in accuracy after error commission. Groups did not differ on these measures, in agreement with numerous previous reports of differences between groups on the ERN amplitude but not on the post-error slowing effect [21,26,27,54] and which suggests a preserved post-error adaptation effect in both groups.

Although there were no differences between groups on behavioral measures, we found that the numerical Stroop task took more time and induced more errors than the classical one, suggesting perhaps that the numerical task was slightly more difficult. Consequently, it might be the case that amplitude differences in the groups' ERN in this task were not only due to its numerical nature but also to its level of difficulty. Two findings argue against this interpretation. Firstly, behavioral measures showed that both groups needed approximately the same time to answer to the numerical task and committed approximately the same number of errors on it. Consequently, nothing suggests that the numerical task was more difficult for the HMA than for the LMA group. Secondly, previous research suggests that the increased difficulty of the task has no effect on the ERN or, if anything, it reduces ERN amplitudes. For example, Pailing and Segalowitz (2004) showed that tasks with higher error rates did not lead to a significantly larger or smaller ERN when compared to tasks with lower error rates [55]. According to this evidence, the fact that the numerical Stroop task was the one with higher error rates does not explain the larger ERN amplitude we found on it. However, a very recent study by Kaczkurkin (2013) showed that increasing task difficulty during a flanker task attenuated ERN amplitudes and enhanced CRN amplitudes, in direct contrast to our findings (enhanced ERN for the more difficult numerical task) [56]. Consequently, we consider that we can rule out the possibility that the ERN differences in amplitude in the numerical task could be attributed to task difficulty.

So, what does this enhanced ERN in the HMA group show? As we mentioned in the introduction, the functional significance of the ERN is still unclear. Two of the most important theories attempting to explain the meaning of the error-related negativity are the conflict monitoring theory and the reinforcement learning theory. Both theories contend that the variation of the magnitude of the ERN is predicted by behavioral measures, so the more frequent errors give rise to decreased ERN and the degree of post-error slowing is related to the magnitude of the ERN [57,58]. Contrarily to these claims, in our study, more frequent errors (errors in the numerical task) generated an increased ERN; the difference was unaccompanied by changes in behavioral or post-error measures, suggesting no relationship between this ERN component and current or subsequent behavior. For this reason, these theories seem unsuitable for explaining our results.

However, the lack of differences in behavioral measures does not necessarily mean that both groups were dealing with the task identically: it might be that the HMA required greater effort in order to show a comparable level of performance in the numerical task to their LMA counterparts. This is exactly what the processing efficiency theory [59] and its extension, the attentional control theory [60], predict. According to these theories, anxiety influences *processing efficiency* (relationship between task performance and the amount of attentional resources spent on solving it) to a greater extent than *performance effectiveness* (quality of task performance). This effect is explained as a consequence of a deficient attentional control in anxious people, which would allow the attentional resources to be allocated to internal threatening stimuli (i.e., worrying thoughts) and consequently reducing the resources devoted to solving the task in hand. As a result, in order to compensate for this resource depletion, anxious people would increase their cognitive effort. Previous evidence has suggested that errors, being associated with cognitive as well as affective correlates, may reflect this effect of increased effort [31]. More specifically, the attentional control theory predicts that errors in high anxious individuals not only imply a *quantitative* difference between anxious groups (enhanced ERN for the high anxious group compared with the low anxious group), but also a *qualitative* difference, which would imply a different pattern of neural activity for the high anxious group, especially in areas involved in emotion processing and cognitive control. In this sense, while most studies have shown quantitative differences between anxious groups [17,18,21,61] others have also found very interesting qualitative differences [31]. For example, Aarts and Pourtois (2010) showed a different configuration of intracranial generators for the ERN between low and high-anxious individuals, with the involvement of more dorsal ACC regions for the low-anxious participants (Brodmann areas 24) and more anterior regions for high-anxious participants. In our study, although sLORETA images seem to suggest a trend for HMA individuals to activate more brain structures than their LMA counterparts when they commit a numerical error, strictly speaking differences in voxel activation between groups were not significant.

To conclude this review of the theories aiming to interpret the ERN component, many recent studies have suggested the idea that errors not only provide *cold* cognitive information, but also convey an important emotional significance and affective reaction [10,54,62]. This is the main idea of the motivational theory of the ERN. The bulk of evidence relating ERN and affect come from studies of anxiety. Several studies have reported an enhanced ERN amplitude for high anxious individuals compared with their low anxious peers [18,20,21,61], which is interpreted as reflecting high anxious individuals' greater sensitivity and concern over errors [21,52]. Our study seems to extend those findings to math anxiety by showing an increased ERN for the HMA group compared to the LMA group for the task that was more salient for them. Furthermore, the sLORETA results showed significantly greater voxel activation at the right insula for the numerical task than for the classical task only for the HMA group. Previous research studying performance monitoring had already reported error-related signal increases at the insula [63–68]. The insula has been suggested to be of relevance for interoception, which can be defined as the sense of the physiological condition of the entire body [69–71]. In this respect, in a numerical version of the Stroop task, insular cortex activity was related to errors and sympathetic arousal measured via pupil diameter [72]. Classical theories of emotion posit that this awareness of one's internal bodily states is a key component of emotional experience. Several avenues of research suggest that the altered insular function is a feature of many anxiety disorders [73]. The right insula, in particular, has been associated with the extent of *interoceptive awareness* and discomfort with one's own physiological response (e.g. heart rate) to emotionally valent pictures [74] and anticipation of emotionally aversive stimuli has been shown to activate the right insular cortex [75]. Functional imaging research suggests that activity in the anterior insular cortex, particularly the right insula, may both mediate anxiety sensitivity and play a role in the pathophysiology of phobias. It is well known that errors are salient events that trigger a cascade of central nervous and autonomous changes such as skin conductance response [27], heart rate deceleration [22,23], pupil dilation [76], amygdala activity [62] and potentiated defensive startle reflexes [54]. As a consequence, it could be the case that the activation of the right insula found for the HMA group when committing a numerical error could be suggesting that this type of error could have generated a greater physiological response in HMA individuals, and that the identification of some of these subtle somatic symptoms might have increased their feeling of distress, showing the greater insular activation and the greater ERN amplitude. In this line, Lyons and Beilock, (2012), using functional magnetic resonance imaging (fMRI), reported an association between the insular cortex activation and subjective ratings of math anxiety when participants anticipated an upcoming math task [77]. Given that interoception has been shown to increase with heightened levels of anxiety and thus leads to increased sensitivity to physical pain, these authors interpreted this result as showing that even anticipating the unpleasant event of solving a math task was associated with the activation of neural regions involved in pain processing in HMA individuals. Despite this topic deserves further intensive research, our results could be suggesting that a HMA's brain might perceive a numerical error as painful.

It is worth mentioning that although we did not obtain insular cortex activation for the Pe component, this area has also been shown to be activated at this later stage of error processing [78] for conscious errors. In this case, it has been suggested that the spatio-temporal dynamics comprise a sequence of brain processes in the posterior cingulated (ERN), left insula (Pe component) and right orbito-frontal cortex (post-Pe) [79]. Nevertheless, the studies associating the conscious perception of errors and the insula have been designed to elicit conscious and unconscious errors, and the two types of errors have been analyzed separately. Since the main objective of this study was not to investigate error awareness, we did not distinguish between conscious and non-conscious errors, and this might be the reason why the insula did not show a significant activation for the Pe component in our study.

To sum up, this is the first study showing abnormal error monitoring in individuals high in math anxiety. Our data suggest that HMA individuals seem to be hypersensitive to self-generated errors in numerical tasks, an effect shown by enhanced ERN and increased insular activation exclusively for numerical errors. Hence, our study also provides evidence that the ERN component conveys information beyond simple error detection and also reflects an affective evaluation of errors [16,17]. The fact that errors in numerical tasks are perceived as abnormally salient or aversive probably constitutes a contributory factor in the development and maintenance of math anxiety. These negative feelings may contribute to *global avoidance* [2,80], that is, the documented tendency of HMA individuals to avoid situations that are math intensive, such as the mathematics curriculum during formal education. This avoidance has an undesired effect on performance, given that it reduces their level of expertise in advanced mathematics. Given the importance of mathematics for academic and professional development and the poorer perspectives for those students suffering from math anxiety, this is a topic that deserves intensive investigation.

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Author Contributions

Conceived and designed the experiments: MINP. Performed the experiments: MSP. Analyzed the data: MSP. Contributed reagents/materials/analysis tools: MINP AC. Wrote the manuscript: MSP. Correction of the manuscript MINP: AC.

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Study V

Working paper

Attentional bias in high math-anxious individuals: evidence from an emotional Stroop task

Running head: Attentional bias in math anxiety

Macarena Suárez-Pellicioni,[a, b] María Isabel Núñez-Peña[a,b] & Àngels Colomé [b,c]

a Department of Behavioural Sciences Methods, Faculty of Psychology, University of Barcelona, Spain
b Institute for Brain, Cognition and Behaviour (IR3C), University of Barcelona, Spain
c Department of Basic Psychology, Faculty of Psychology, University of Barcelona, Spain

Correspondence to:
Maria Isabel Núñez-Peña
Department of Behavioural Sciences Methods
Faculty of Psychology
University of Barcelona
Passeig Vall d'Hebron, 171
08035 Barcelona (SPAIN)

Tel. (+34) 93 312 58 53
Fax: (+34) 93 402 13 59
E-mail: inunez@ub.edu

ABSTRACT

Attentional bias towards threatening or emotional information is considered a cognitive marker of anxiety, and it has been described in various clinical and subclinical populations. This study used an emotional Stroop task to investigate whether math anxiety is characterized by an attentional bias towards math-related words. Two previous studies failed to observe such an effect in math-anxious individuals, although the authors acknowledged certain methodological limitations that the present study seeks to avoid. Twenty high math-anxious (HMA) and 20 low math-anxious (LMA) individuals were presented with an emotional Stroop task including math-related and neutral words. Participants in the two groups did not differ in trait anxiety or depression. We found that the HMA group showed slower response times to math-related words than to neutral words, which constitutes the first demonstration of an attentional bias towards math-related words in HMA individuals.

Keywords: attentional bias; emotional Stroop task; math anxiety.

INTRODUCTION

Why do students with similar math ability choose alternative academic pathways at university? LeFevre, Kulak, and Heymans (1992) constructed a regression model to predict students' choices of university majors varying in mathematical content and found that whereas age, fluency in math and experience with math contributed significantly to the choice, a "math affect" factor, comprising math anxiety and measures of avoidance towards math, more than doubled the variance accounted for by the model. Math anxiety has been defined as a feeling of tension, apprehension or even dread that interferes with the ordinary manipulation of numbers (Ashcraft & Faust, 1994). The negative effect of anxiety is reflected in poorer performance among high math-anxious individuals (hereinafter, HMA), which, in turn, generates feelings of failure and, consequently, avoidance of this subject in the academic curriculum. As such, math anxiety leads people who are perfectly capable of doing math to distance themselves from mathematical contents and to feel afraid of the subject.

Although not recognized as a clinical condition, math anxiety is nonetheless a type of anxiety. Indeed, research has shown that findings related to other types of anxiety can be extended to the field of math anxiety. For example, as previously shown for generalized anxiety disorder or obsessive compulsive disorder (e.g., Gehring, Himle, & Nisenson, 2000), a greater *error-related negativity* (i.e., an ERP component appearing approximately 150 ms after error commission) has been found in HMA individuals for errors committed in a numerical Stroop task (Suárez-Pellicioni, Núñez-Peña, & Colomé, 2013). Similarly, the reactive recruitment of attentional control observed for high trait anxious individuals (Osinsky, Gebhardt, Alexander, & Hennig, 2012) was also found for HMA ones, who exerted attentional control only after incongruent trials on a numerical Stroop task (Suárez-Pellicioni, Núñez-Peña, & Colomé, 2014). Finally, several cognitive theories (Williams, Watts, MacLeod, & Mathews, 1988) have postulated that attentional bias towards threatening information can be considered a cognitive marker of numerous types of anxiety (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007), maintaining problematic anxiety reactions by encouraging a state of hyperarousal (Beck, Emery, & Greenberg, 1985).

Attentional bias has traditionally been measured with the emotional Stroop task, in which participants have to report the ink color of threatening (or emotionally charged) and neutral words presented in different ink colors (Williams, Mathews, & MacLeod, 1996). The emotional Stroop effect consists of a slower response time to threatening words than to neutral ones, and this is considered to indicate the allocation of attention to emotional stimuli. This task has been successfully used with several types of anxious patients (e.g., Williams et al., 1996), while in non-clinical populations the largest emotional Stroop effects are usually observed for those stimuli that relate to the participants' concerns or worries. Following this line of research, we were interested in finding out whether HMA individuals would take longer to respond to the color of math-related words than to that of neutral ones.

Despite the infancy of research on math anxiety, two studies (Hopko, McNeil, Gleason, & Rabalais, 2002; McLaughlin, 1996) have already tried to answer this question by means of the emotional Stroop task. First, in a study that used a paper version of the Stroop task including math-related and neutral words, McLaughlin (1996) found no increase in response times to math-related words for HMA individuals. However, groups were formed using a split-half subject sample based on the mean math anxiety score, which means that the groups were not representative of extreme high and low math anxiety. Moreover, computer presentations of the task have been shown to be more powerful than the paper-and-pencil format for assessing Stroop-related effects (MacLeod, 1991). Given these methodological limitations, Hopko and collaborators (2002) later employed the same task but they formed the groups to be extreme on math anxiety scores (top and bottom 20% of their same-gender distribution). Furthermore, they used a computer-based version of the task in which each participant was presented with Stroop screens containing 100 words displayed in five different colors. Despite the authors' efforts to overcome the methodological limitations of the study by McLaughlin (1996), they still found no differences in response times, neither between groups nor between types of words. They acknowledged that this might have been due to the type of math-related words they used, which were probably too abstract (e.g., polynomial, theorem) and, therefore, less familiar to HMA individuals, who due to their math avoidance, tend not to enroll in advanced courses. Moreover, response latencies were calculated for each screen (i.e., 100 words), whereas calculating RTs separately for each word would probably have been a more sensitive method.

Within this context, the objective of the present study was to demonstrate an attentional bias towards math-related words in HMA individuals, which would constitute the first step towards further investigation of this bias as a possible mechanism by which math anxiety may originate, be maintained and/or become aggravated. To achieve this objective we took steps to avoid the methodological limitations that most likely prevented previous researchers from observing significant results. Thus, following Hopko et al. (2002) we formed extreme groups and used a computer-based version of the task. In addition, we presented words individually in order to obtain a more accurate measure of response times, and we used more familiar math-related words. Moreover, we made sure that participants did not differ in trait anxiety, such that any differences between groups could not be explained by this variable. Finally, at the end of the experiment, participants were asked to provide a self-report measure of perceived anxiety to each stimulus.

METHODS

Participants

Forty healthy volunteers were tested in this study, half of them with a high level of math anxiety (HMA) and the other half with a low level (LMA). They were selected from among a sample of 629 students from the University of Barcelona who were assessed for math anxiety and trait anxiety (see Materials) in the context of a larger project.

The LMA group comprised 20 participants (mean age = 21.95, SEM = .73) who scored below the first quartile (mean = 44.95, SEM = 1.53) on the Spanish version of the Abbreviated Mathematics Anxiety Rating Scale (sMARS). The HMA group also comprised 20 participants (mean age = 21.70, SEM = .63), all of whom scored above the third quartile (mean = 86.40, SEM = 1.31) on the sMARS. No participant was excluded from the study.

All participants had low scores on the Spanish version of the Zung Self-Rating Depression Scale (Conde & Escribá, 1970) (mean = 30.68, SEM = 1.03, range = 22-49), indicating that no participant should be classified as depressed.

Groups differed in math anxiety ($t(38) = 19.90$, $p < .001$) but not in trait anxiety ($t(38) = 1.12$, $p = .26$), depression ($t(38) = 1.24$, $p = .22$), age ($t(38) = .25$, $p = .79$), years of formal education ($t(38) = 1.01$, $p = .31$), handedness ($\chi^2 = .36$, $p = .54$), or ethnicity ($\chi^2 = 1.02$, $p = .31$).

Materials

Screening phase: Participants were administered the following instruments:

Abbreviated Mathematics Anxiety Rating Scale (sMARS). This instrument measures math anxiety by presenting 25 situations which may cause math anxiety. The present study used the Spanish version of the sMARS (Núñez-Peña, Suárez-Pellicioni, Guilera, & Mercadé-Carranza, 2013), which has shown strong internal consistency (Cronbach's alpha = .94) and high 7-week test-retest reliability (intra-class correlation coefficient = .72).

State-Trait Anxiety Inventory (STAI). Only the trait anxiety subtest was used. This includes 20 statements describing different emotions. Respondents have to answer by considering how they feel 'in general'. The Spanish version of this test, which has shown good psychometric properties (Spielberger, Gorsuch, & Lushene, 2008), was used in this study.

Experimental session: Pretest

Participants were administered the following scale:

Zung Self-Rating Depression Scale: This scale contains 20 statements. Respondents have to rate the items according to how they apply to him/her over the last few days, using four response options reflecting the frequency of occurrence. Total scores range from 20 to 80, and a score below 49 is considered to indicate no depression. The present study used the Spanish version of this test (Conde & Escribá, 1970), which shows good internal consistency

(Cronbach's alpha = .79 - .92) and good validity evidence (correlation with the Hamilton and Beck depression scales ranging from .50 to .80).

Experimental session: *The emotional Stroop task*

Fourteen neutral words and 14 math-related words were used in the experiment (stimuli are listed in the Appendix). The words were obtained through a questionnaire administered to 117 year-two students from the Faculty of Psychology of the University of Barcelona. This questionnaire asked participants to write down the first 15 words that came to mind when thinking about mathematics. From this information we selected the 14 words that were most reported by students as being math-related. We then selected 14 neutral words from the Spanish lexical database of NIM (Guasch, Boada, Ferré, & Sánchez-Casas, 2013) that matched the math-related words on several characteristics. Consequently, words in the two categories did not differ in frequency ($t(26) = .02$, $p = .97$), number of phonemes ($t(26) = .08$, $p = .93$), familiarity ($t(22) = .38$, $p = .70$), imageability ($t(22) = 1.04$, $p = .30$), or concreteness ($t(22) = .71$, $p = .48$).

The two types of words were presented in separate blocks, since this approach has been found to generate larger overall RT interference than do mixed stimuli (Holle & Neely, 1997). Each block included 58 stimuli: 2 fillers (excluded from the analysis) followed by 56 stimuli corresponding to the 14 stimuli presented in the 4 ink colors. Stimuli in each block were presented pseudo-randomly, with the only restriction being that the same ink color was never presented in two consecutive trials. Blocks were presented randomly to each participant and were separated by one minute rest.

Experimental session: Post-test

At this point, participants were administered the self-report questionnaire, which asked them to rate the level of anxiety generated by each stimulus. There were five response options, ranging from 1 (*Nothing*) to 5 (*A lot*). Participants were told to respond by taking into account their thoughts and feelings while performing the emotional Stroop task.

Procedure

Participants were tested individually. The session began with a training block of 20 words, all of them neutral and different from the ones presented in the experimental session. When participants achieved 65% of hits in the training period, the experimental session started.

Stimuli were presented at the center of a black screen in font type Tahoma (size 35) and in four different ink colors (red, blue, green, and yellow). The task for participants consisted in responding to the ink color of the stimuli by means of a button press, as fast and as accurately as possible. Participants responded with the index and middle finger of each hand, using a keyboard and setting their fingers on the response buttons. Response buttons were color-coded with a sticker so that “red”, “blue”, “green”, and “yellow” responses corresponded, respectively, to the letters “d”, “f”, “j”, and “k” on the keyboard. Each trial began with a fixation sign (an asterisk) shown for 500 ms. After that, a word was presented on the screen and remained there until a response was given (maximum of 1500 ms). Each trial was followed by a variable inter-trial interval ranging from 1000 ms to 1600 ms (a black screen).

DATA ANALYSIS AND RESULTS

Behavioral measures

Trimmed means (5%) of response times were calculated for correctly solved trials, separately for each condition and for each participant. The trimming procedure controlled for the effects of outliers by removing 2.5% of scores from both the upper and lower bounds of each participant’s distribution. Percentages of hits were also calculated for each participant in each condition. Response times and percentage of hits were analyzed through analyses of variance (ANOVAs), taking *Stimuli* (math-related word and neutral word) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor. The *F* value, the uncorrected degrees of freedom, the probability level following correction, the ε value (when appropriate), and the partial eta square index (η_p^2) are given. We performed tests of simple effects when an interaction was significant, and used the Bonferroni correction to control for the increase in Type I error.

Regarding response times, we found a significant main effect of *Group* ($F(1,38) = 4.57$, $p = .03$, $\eta_p^2 = .10$), with the HMA group being slower than the LMA one. More interestingly, we found a significant *Stimuli x Group* interaction ($F(1,38) = 4.24$, $p = .04$, $\eta_p^2 = .10$). Simple effects analyses showed that the HMA group took longer to respond to math-related words than to neutral ones ($t(19) = 2.37$, $p = .02$), whereas no difference emerged for the LMA group ($t(19) = .51$, $p = .61$). On the other hand, when comparing groups for each condition we found that groups differed when responding to math-related words ($t(38) = 2.66$, $p = .01$), with the HMA group being slower than the LMA one; however, this group differences were not observed when responding to neutral words ($t(38) = 1.42$, $p = .16$).

Regarding the percentage of hits, no main effects or interaction reached significance (all *p* values above .25). Means and SEM for response times and percentage of hits for each group and for each stimulus are shown in Table 1.

Table 1. Means of RT (SEM in brackets) for behavioral and self-reported measures in relation to math-related and neutral words and for their difference (math-related – neutral) for the LMA and HMA groups.

	LMA			HMA		
	Math-related	Neutral	Difference	Math-related	Neutral	Difference
RT	589.72 (19.46)	595.65 (19.59)	-5.93 (11.51)	663.05 (19.46)	635.09 (19.59)	27.95 (11.74)
Accuracy	94.50 (.82)	93.14 (.89)	1.35 (.90)	93.90 (.82)	94.00 (.89)	.10 (.89)
Self-reported level of anxiety	16.20 (1.84)	15.75 (.96)	.45 (.49)	31.05 (1.84)	16.65 (.96)	14.40 (2.28)

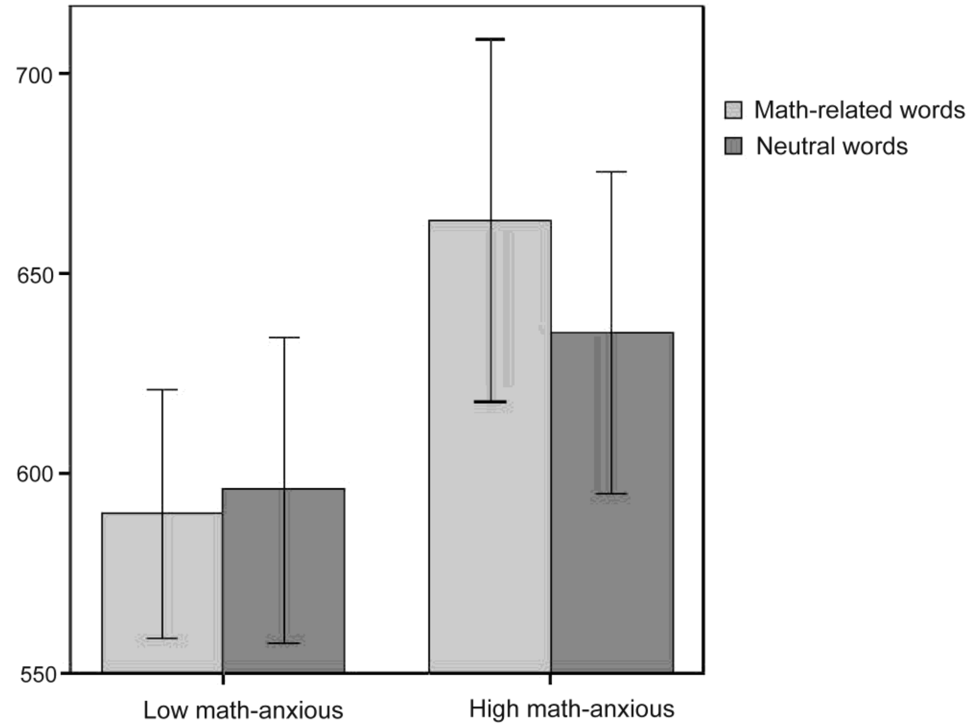

Figure 1. Trimmed means and standard errors (in bars) for response times (in ms) for the LMA and HMA groups when responding to neutral and math-related words.

Self-reported level of anxiety

An ANOVA was performed taking *Stimuli* as the within-subject factor and *Group* as the between-subjects factor. The ANOVA showed a significant *Stimuli* x *Group* interaction ($F(1,38) = 35.55$, $p < .001$, $\eta_p^2 = .48$): specifically, the HMA group reported a higher level of anxiety for math-related words as compared with neutral words ($t(19) = 6.29$, $p < .001$) whereas no such difference was observed for the LMA group ($t(19) = .91$, $p = .78$). When stimuli assessment was compared across groups, they were found to differ for math-related words ($t(38) = 5.70$, $p < .001$), but not for neutral words ($t(38) = .66$, $p = .51$), with the HMA group reporting higher levels of anxiety than the LMA group. Means and SEM for these self-reported measures are shown in Table 1.

DISCUSSION

This study used an emotional Stroop task to investigate the existence of an attentional bias in math anxiety, the aim being to provide initial evidence for a possible mechanism by which math anxiety may originate, be maintained and/or become aggravated. In order to achieve this objective we designed an experiment that sought to overcome the methodological limitations that may have prevented previous researchers from observing the emotional Stroop effect in HMA individuals. The main methodological improvements were: 1) groups were formed according to extreme scores on math anxiety; 2) we used a computer-based task; 3) words were presented individually; 4) math-related words were carefully selected to be significant for our sample; 5) several subject variables were controlled for; and 6) self-report measures were included in order to assess perceived anxiety towards each stimulus.

Our results showed, first, that HMA individuals needed longer to report the ink color of math-related words as compared with neutral words, whereas no such difference emerged for their LMA counterparts. This difference shows that participants noticed the meaning of the irrelevant dimension of the task (i.e., stimulus content) and that this math-related content prolonged the time that HMA individuals needed to name the color in which the stimulus was printed, as compared with a neutral stimulus. The question is: what lies behind this delay in response time?

Traditionally, the slowdown observed when comparing threatening vs. neutral information has been explained as an *attentional bias* towards threatening or emotional information (Williams et al., 1996). Previous research in other types of anxiety has demonstrated attentional bias for those words related to the current concerns of the participant or patient. For example, panic disorder participants were slower to color-naming physical threat words (Hope, Rapee, Heimberg & Dombeck., 1990), rape victims with post-traumatic stress disorder showed delayed response times for color naming rape-related words (Foa, Feske, Murdock, Kozak, & McCarthy, 1991), high dental anxious subjects were slower in color-naming dentist-related words (Muris, Merckelback, & Jongh, 1995) and social phobics showed longer latencies for reporting the ink color of social threat words (Holle & Neely, 1997). Our study extends these findings to the field of math anxiety by demonstrating that HMA individuals also show an attentional bias towards math-related words. According to this, HMA individuals' attention would have been directed to process math-related words' content, and thus, deviated for the main task of reporting their ink color.

Nevertheless, the mechanisms underlying this attentional bias remain the subject of debate. In this respect, according to the *facilitated attention account*, emotional stimuli are noticed earlier than neutral stimuli (i.e., preferential engagement) and command attention at the expense of other stimuli or dimensions of the stimulus (i.e., ink color) (Pratto & John, 1991; Williams et al., 1996). Consequently, the emotional Stroop effect is the product of the disproportionate amount of attention captured by emotional words, attention that would otherwise have been directed to performing the main task (i.e., naming the ink color). The *difficulty in disengagement account*, by contrast, argues that once attention is allocated towards a threat stimulus, it is held longer than in the case of neutral stimuli, thereby disrupting the processing of other stimulus properties and delaying the time needed to report the ink color (Fox, Russo, Bowles, & Dutton, 2001).

Unfortunately, the emotional Stroop task does not allow us to distinguish which of these two components of attentional bias is responsible for the observed delay in response times. Thus, it could be the case that HMA individuals showed facilitated attention towards math-related content, such that the word "*fórmula"* (i.e., formula) captured more of their attention than did the word "*calzado"* (i.e., footwear), with the amount of attention that was drawn away from the main task causing the delay in response times. However, it is also possible that HMA individuals showed no preferential engagement but, rather, found it difficult to disengage their attention from math-related information, in which case the word "*fórmula"* would have held attentional resources for longer than did the word "*calzado"*, thereby explaining why they needed longer to respond to the former stimulus. Further research is now needed to determine which of these two alternatives offers the best explanation for attentional bias in high math-anxious individuals.

To summarize, this study constitutes the first evidence that an attentional bias is present in HMA individuals. This "inclination" towards math-related information merits further research in order to determine whether it may play a role in the origin, maintenance and/or aggravation of math anxiety, as well as the exact mechanisms underlying it.

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Appendix

Spanish Word	English translation	Frequency	Number of phonemes	Familiarity	Imageability	Concreteness
Neutral words presented in the training session						
Jungla	Jungle	3.57	6	5.35	6.22	4.96
Jugador	Player	97.00	7	5.95	5.97	4.76
Máquina	Machine	37.93	6	5.98	5.56	4.24
Camino	Path	209.90	6	5.97	6.10	4.75
Empresa	Company	164.22	7	5.84	5.07	5.17
Math-related words presented in the experimental session						
Álgebra	Algebra	4.41	7	-	-	-
Cálculo	Calculus	23.95	7	5.01	3.34	4.04
Ecuación	Equation	13.17	8	5.08	5.61	4.85
Matemáticas	Mathematics	20.92	11	5.62	4.75	5.21
Estadística	Statistics	18.06	11	5.71	3.3	4.36
Fórmula	Formula	42.21	7	4.97	4.64	4.25
Geometría	Geometry	10.90	9	3.89	3.30	4.50
Logaritmo	Logarithm	0.65	9	-	-	-
Multiplicación	Multiplication	5.60	14	-	-	-
Número	Number	341.66	6	6.50	6.48	5.04
Resta	Subtraction	6.10	5	5.98	3.92	4.94
Suma	Addition	53.12	4	5.91	4.7	4.84
División	Division	123.19	8	5.40	5.34	4.16
Calculadora	Mathematical calculator	1.75	11	-	-	-
Neutral words presented in the experimental session						
Silueta	Silhouette	4.48	7	4.09	5.88	4.92
Respaldo	Back	24.21	8	5.39	4.66	5.09
Inscripción	Registration	13.42	11	5.72	4.95	4.89
Empresario	Entrepreneur	21.27	10	5.41	5.70	5.19
Funcionario	Civil servant	19.14	11	5.43	4.80	4.57
Patria	Homeland	42.05	6	4.49	3.95	4.98
Trayecto	Journey	10.91	8	5.22	4.48	4.68

Recibidor	Reception	0.71	9	5.17	5.05	4.46
Sugerencia	Suggestion	5.80	11	4.24	4.42	4.56
Población	Population	324.75	9	5.77	4.91	4.41
Calzado	Footwear	6.13	7	5.99	5.77	5.03
Ruta	Route	54.20	4	5.82	5.43	5.0
Reforma	Refurbishment	123.05	7	6.10	4.75	4.21
Simulacro	Simulation	1.55	9	4.25	4.55	4.56

GENERAL DISCUSSION

The contribution of this thesis

The main objective of this thesis was to explore more deeply the difficulties HMA individuals face when they have to perform a task involving numbers, by means of the ERP technique. More concretely, this thesis comprised five studies aiming to: (1) adapt into Spanish and validate the sMARS scale (Study I), (2) study the use of the plausibility strategy in math-anxious individuals by replicating Faust et al. (1996)´s finding on *flawed scores* while recording participants´ electrical brain activity with the ERP technique (Study II), (3) study the electrophysiological correlates of numeric interference in math-anxious individuals (Study III), (4) study the processing of errors in LMA and HMA individuals with the ERP technique (Study IV) and (5) study the attentional bias towards math-related information in MA in order to find out whether MA is characterized by the same mechanisms considered to play an important role in the etiology and maintenance of other types of anxiety (Study V).

In our first study, the adaptation into Spanish of the sMARS scale gave sound evidence of its good psychometric properties: strong internal consistency, high 7-week test-retest reliability and good convergent/discriminant validity. Moreover, the confirmatory factor analysis showed that the three dimensions (i.e. math test, numerical task and math course anxiety) established in the original sMARS proposed by Alexander and Martray (1989) were also evident in the Spanish version. This first study was necessary, as a starting point of the other studies comprising this PhD thesis, to make sure that MA will be measured with an instrument providing reliable and valid measures of this construct. As a result, we validated a scale for Spanish-speaking population that could be used not only for research ends, but also in educational contexts, as a practical and short way to assess students´ level of MA, in order to detect those high in MA and adapt the math course dynamics and evaluation to them.

The second study aimed to reproduce previous findings on *flawed scores* (Faust et al., 1996) with the help of the more sensitive ERPs technique, which would let us give support to Faust et al. (1996)'s results on HMA individuals' difficulties in processing *large-split* solutions. First of all, we reproduced Faust et al. (1996)´s *flawed scores* pattern, what gave support to this finding itself, which had never been replicated before. Moreover, the use of ERPs allowed us to discover that *large-split* solutions generated a P600/P3b component of larger amplitude and delayed latency for the HMA group as compared to the LMA one. Given that the amplitude of this component is linked to the devotion of processing resources to the task (Salisbury, Rutherfor, Shenton, & McCarley, 2001) and its latency is considered to index the speed of stimulus processing (Verleger, 1997), these findings suggested that *large-split* solutions demanded more cognitive resources and required more time to be processed for the HMA group than for the LMA one, making them less efficient.

Indeed, this is the main claim of the Processing Efficiency Theory (Eysenck & Calvo, 1992), one of the most important theories trying to explain the negative effects of anxiety on performance. According to the PET, anxiety affects processing efficiency (i.e. quality of performance in relationship with the amount of resources spent to achieve that level of performance) to a greater extent than performance effectiveness (i.e. quality of performance *per se*), which implies that high anxious individuals have to make a greater effort (i.e. use greater amount of resources) to achieve the same level of performance than low anxious individuals. A subsequent adaptation of this theory, named the ACT (Eysenck et al., 2007), claimed that anxiety impairs processing efficiency because it reduces attentional control, since it decreases the influence of the *goal-directed attentional system*, which is influenced by expectations, knowledge and current goals (i.e. top-down control of attention) and increases the influence of the *stimulus-driven attentional system,* which responds maximally to salient stimuli (i.e. bottom-up control of attention) (Corbetta & Shulman, 2002). Thus, high anxious individuals, being more influenced by the stimulus-driven attentional system, would find it difficult to resist disruption from salient or conspicuous stimuli, and consequently, would be more easily distracted than their low anxious counterparts.

We interpreted our result in the context of this theory: when HMA individuals were presented with a dramatically incorrect solution, instead of responding a quick “no” (i.e. plausibility strategy), they would have succumbed to the salient nature of this impossible solution, devoting more resources and more time to process it as compared to the LMA group. These findings were obtained after a deeper examination of the *flawed scores* pattern, which constituted the first clue suggesting HMA individuals’ differential processing of *large-split* solutions. In this respect, these scores were an ingenious and useful way of measuring differences in processing, or, in Faust et al. (1996)’s own words: “difficulties in processing”. Indeed, the use of ERPs to explore this finding showed us that the process underlying it has to do with HMA individuals devoting more time and resources to the processing of these dramatically incorrect solutions, which, according to our interpretation, was due to its salient nature. Indeed, previous evidence had already shown that HMA individuals are more influenced by distracting information as compared to LMA ones both in reading paragraphs containing distractor words (Hopko et al., 1998) and in a Stroop task in which participants had to respond to the quantity of numbers presented while ignoring its magnitude (Hopko et al., 2002).

Given these evidences, Study III aimed to further investigate this vulnerability to distraction by means of another type of numeric Stroop task and, again, with the help of the ERP technique. In this version of the Stroop task, participants experience a conflict when they have to respond to the relevant dimension of the stimulus while its physical size acts as a distractor. By studying how HMA individuals process conflicting stimulus (i.e. incongruent trials) as compared to non-conflicting ones (i.e. congruent ones), by means of the ERP technique, we would be able to obtain more specific information about possible group differences in the different stages of conflict processing, what would allow us to explain the greater interference in RTs found for HMA individuals in previous studies (Hopko et al., 1998; 2002).

In line with previous research, we found that HMA individuals needed more time to respond to incongruent trials as compared to congruent ones, that is, were slower to solve the conflict, as compared to their LMA peers, suggesting that HMA individuals were more distracted by the task-irrelevant dimension of the stimuli (i.e. number's physical size). By analyzing ERP data we found differences between groups in the conflict adaptation effect (i.e. level of current interference depending on the congruence of the previous trial). More concretely, we found that: 1) the LMA group showed a N450 component of greater amplitude (i.e. showing greater interference) for the interference effect preceded by congruence than when preceded by incongruity while no differences were shown for the HMA group, and 2) the HMA group showed a CSP of greater amplitude (i.e. showing greater interference) for the interference effect preceded by congruence than when preceded by incongruity, while no differences emerged for the LMA one.

We interpreted these findings in the context of the *Conflict monitoring model* (CMM; Botvinick et al., 2001) and the *Dual mechanism of control account* (DMC; Braver, Gray, & Burgess, 2007). On the one hand, according to the CMM, when an incongruent trial is presented, a simultaneous activation of competing responses (i.e. response conflict) is produced. This conflict is detected by a conflict-monitoring mechanism, thought to reside in the ACC, which triggers an up-regulation in cognitive control, thought to be implemented by the dorsolateral prefrontal cortex (DLPFC), in order to overcome the conflict. Given that previous evidence has shown that the N450 is generated by the ACC and the CSP by the LPFC (West, 2003), the N450 is taken to show conflict detection and the CSP the implementation of cognitive control. On the other hand, according to the *Dual mechanisms of control* account, this cognitive control is exerted in different ways depending on the level of anxiety: low anxious individuals are considered to exert top-down control in a *proactive way*, which implies a sustained representation of task requirements or goals over time and which constitutes a more effective control of attention (i.e. goal-directed attentional system), preventing conflict during ongoing processing; In contrast, high anxious individuals are considered to exert attentional control in a *reactive way*, which implies that, after task goals are first coded, they are not maintained in a continuously active state, but activated only when needed (e.g. when conflict occurs), which makes processing more vulnerable to the influence of bottom-up input (i.e. the stimulus-driven attentional system).

In this context, our study showed differences in the way math-anxious groups detected and responded to conflict: on the one hand, LMA individuals presented the expected conflict adaptation effect in the first stage of conflict detection, suggesting that they perceived a greater level of interference when it was preceded by a congruent trial than when it was preceded by an incongruent one, indicating that the previous incongruent trial may have enhanced cognitive control, what would have made them perceive less conflict). Nevertheless, after this initial phase of conflict detection, the proactive execution of attentional control would have made them show the same reduced level of interference regardless of the congruence of the previous trial (as shown by the same reduced CSP amplitude regardless of previous trial congruence). On the other hand, the HMA group did not show a conflict adaptation effect on a first stage of conflict processing (i.e. the N450 having the same amplitude both when preceded by congruence that by incongruity), suggesting that they detected the same level of interference regardless of the congruence of the previous trial. Furthermore they exerted control in a reactive way in a subsequent stage of conflict processing, paying attention only when the previous trial was incongruent (i.e. CSP amplitude similar to LMA individuals) but not when it was congruent (i.e. enhanced CSP, signaling greater level of interference). The differential level of interference reflected by the CSP's amplitude for the HMA group (but not for the LMA one), made us suggest that attentional control was exerted differently by HMA individuals as compared to LMA ones. These findings are consistent with the DMC account (Braver et al., 2007), which, as commented earlier, is based in two main claims: first, high anxious individuals exert attentional control only when they find it is needed and second, the consequences of exerting attentional control in that way is that they become more vulnerable to distraction. In this study, we found that HMA individuals exerted attentional control only after incongruent trials (implying conflicting information), this reactive way of exerting attentional control probably being at the base of their greater vulnerability to distracting information. In this respect, although we expected to find a correlation between CSP amplitude and the interference effect in RTs, what would suggest that HMA individuals' greater interference was due to this lack of increase in cognitive control after congruent trials (i.e. CSP enhancement), this correlation did not reach significance. However, we found that the greater the CSP amplitude when preceded by congruence, the greater the interference in hit rates (i.e. more errors were committed) both when preceded by congruence and when considered it in general (regardless of previous congruence).

These results seem to be in line with previous evidence reporting that the extent of HMA individuals´ deficits in mathematics could be predicted by how cognitive control resources were recruited when they anticipated a forthcoming math task (Lyons & Beilock, 2012a). In other words, they found that the reduced math deficits exhibited by some HMA individuals were the result of these individuals ramping up cognitive control resources when anticipating math in a manner that allowed them to change the way they approach performing the upcoming math task. Thus, in the same way that ramping up cognitive control resources when anticipating a math task implied a better performance in HMA individuals, the fact that they did not exert cognitive control after congruent trials in a numeric Stroop task would be at the base of their drop in accuracy (i.e. the greater the CSP amplitude the worse the level of performance in the task).

The two remaining studies of this PhD thesis aimed to explore two possible factors contributing to the development of MA. Study IV aimed to assess whether LMA and HMA individuals differed in the way they process a numeric error as compared to a non-numeric one, by analyzing the ERN component. This component has been suggested to reflect motivational or emotional reaction to errors (Hajcak & Foti, 2008), with several findings reporting that it shows a greater amplitude for more significant errors (e.g. Kim et al., 2005) and for several anxious samples characterized by an increased sensitivity to errors, like in patients with obsessive-compulsive disorder (Gehring et al., 2000). Given the processes considered to be reflected by this component, it constitutes a great candidate to reveal possible differences in the emotional implications of numeric errors in HMA brains.

In this line, we found that HMA individuals showed an increased ERN when they committed an error in a numeric Stroop task, but not in a classical Stroop task, while no differences emerged for the LMA group (showing the same reduced component for both tasks). Moreover, this finding was specific for errors, while no differences emerged for the correct responses (i.e. CRN). We interpreted this finding in the context of the Motivational Significance Theory (Hajcak & Foti, 2008), the greater ERN for numeric errors only for the HMA group showing their greater sensitivity, concern or emotional reaction about having committed an error in a numeric task, as compared to a task not involving numbers. In this respect, sLORETA analysis' results pointed in the same direction. This analysis showed that while no differences were found for the brain sources of the ERN in the two tasks for the LMA group, the commission of a numeric error in HMA individuals implied a greater right insular activation, as compared to a non-numeric one.

The insular cortex is centrally placed to receive information about the salience (both appetitive and aversive) and relative value of the stimulus environment and integrate this information with the effect that these stimuli may have on the body state (Paulus & Stein, 2006). Moreover, there is sound evidence of altered insular functioning in patients with anxiety disorders (e.g. Paulus & Stein, 2006). More concretely, the right insula has been found to show an exaggerated response to fearful faces in individuals with specific phobia (Wright, Martis, McMullin, Shin, Rauch, 2003), to be related to the discomfort with one´s own physiological responses to emotionally stimuli (Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004) and to the anticipation of emotionally aversive stimuli (Paulus, Rogalsky, Simmons, Feinstein, & Stein, 2003). Given that errors are considered to generate a cascade of central nervous and autonomous effects (e.g. skin conductance response (Hajcak, McDonald, N., & Simons, 2003), heart rate deceleration (Hajcak, McDonald, & Simons, 2004), pupil dilation (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005), etc.) and that the right insula shows the discomfort with this kind of physiological responses, we interpreted these findings as showing that numeric errors not only would have been perceived as more significant by HMA individuals, but they may have caused physiological responses that would have been perceived as threatening or unpleasant by individuals high in MA.

In this respect, it would have been very interesting to have registered these physiological reactions towards errors in our participants (e.g. heart rate, skin conductance, etc.), as Faust (1992) did while LMA and HMA individuals performed a numeric task of increasing difficulty, in order to have a definite evidence of the physiological responses that we claim that are at the base of the ERN enhancement and right insular activation in HMA individuals. Similarly, it would be interesting for future research to collect information about self-reported measures of the perception of somatic sensations when a numeric and non-numeric errors are committed by LMA and HMA individuals, by using self-reported questionnaires, such as the Body Vigilance Scale (Schmidt, Mitchell, & Richey, 2008), the Body Sensations Questionnaire (Chambless, Caputo, Bright & Gallagher, 1984) and even a questionnaire assessing participants' interpretation of these sensations, like the Body Sensations Interpretation Questionnaire (Clark, Salkovskis, Ost, Breitholtz, Koehler, Westling, 1997). By including these measurements, future studies may find increased self-reported measures of body sensations in HMA individuals when committing a numeric error. Indeed, this is the common finding in several anxiety disorders, in which high anxious individuals not only report increased somatic sensations, but also a subsequent dysfunctional cognitive appraisal of these sensations with a significant bias towards a catastrophizing interpretational style (Beck et al., 1985). In this line, previous evidence has suggested that it is not the physiological reactions *per se*, but rather the interpretation of these reactions what determines the emotions (Schachter & Singer, 1962). According to Schachter and Singer's theory of emotion, individuals perceive an emotional event based on the cognitive interpretation they make of internal physiological cues. For example, if a person experiences sweating palms and a racing heart, this theory argues that one´s interpretation of these cues discriminates between the subjective feeling of fear and that of love.

In this respect, in the field of MA, the interpretation of these physiological responses in stressful situations has been found to determine whether these responses will be disruptive or beneficial to performance. Mattarella-Micke, Mateo, Kozak, Foster, and Beilock (2011) collected data about participants´ WM capacity and MA and sampled their salivary cortisol concentrations (an hormone associated with stressors in humans), as a measure of their physiological response while they performed a Modular arithmetic task (e.g. "51 Ξ 19 (mod 4)"), in which participants have to subtract the middle number (i.e. 19) from the first one (i.e. 51) and then divide the difference by the last one (i.e. 4). The correlational analysis showed that for individuals with higher WM capacity, the level of MA determined the relationship between concentrations of cortisol and level of performance: for HMA individuals, as the concentration of cortisol increased (i.e. greater physiological response), the level of performance decreased, while for LMA ones, as the concentration of cortisol increased, also did the level of performance. They interpreted these results as showing the importance of one's interpretation of physiological responses, a negative interpretation leading HMA individuals to perform poorly while a positive (or at least non-threatening) interpretation in LMA ones would have helped them succeed in the task. In this line, and turning back to our own results, it may be the case that a threatening or negative interpretation of the physiological responses generated by a numeric error in HMA individuals (instead of more intense physiological responses) could be at the base of their greater ERN component and right insular activation.

Finally, Study V aimed to investigate an attentional bias towards math-related information in order to have evidence of a bias that has been recognized as an important factor in the development and maintenance of anxiety (Mathews & MacLeod, 2002), and thus, that may play a role in the development of MA. Indeed, this attentional bias has been demonstrated in generalized anxiety disorder (Bradley et al., 1999), social phobia (Amir et al., 2003), post-traumatic stress disorder (Bryant & Harvey, 1995), specific phobia (Öhman et al., 2001), panic disorder (Buckley et al., 2002) and obsessive compulsive disorder (Cisler & Olatunji, 2010). In this context, it is possible that HMA individuals show an attentional bias towards math-related information and that this bias, as shown for other types of anxiety, would play some role in its origin and/or development. By improving some methodological limitations and by means of an emotional Stroop task (the same task used by previous researchers), we found that HMA individuals were slower to process math-related words as compared to neutral ones. This slowdown in an emotional Stroop task has traditionally been interpreted as an attentional bias towards threatening or emotional stimuli. Thus, our study constitutes the first evidence showing that an attentional bias is present in MA and that this "inclination" of HMA individuals towards math-related information may play a role in the origin or maintenance of this condition. For example, it has been suggested that an enhanced tendency to select threatening items for processing is likely to lead to an artificially increased perception of the extent of threat in the environment, thereby enhancing anxious mood (Mathews, 1990). Nevertheless, there still are several questions that remain to be explained in this respect such as how this math-related information impacts HMA individuals´ attention: does this information show a preferential engagement of attention as compared to math-unrelated information? Does this information held attention longer than math-unrelated one, so HMA individuals show a difficulty in disengaging from it? Future research needs to be done by means of other tasks like the spatial cueing, visual search or dot probe tasks, in order to clarify among these possible explanations.

Very interestingly, one of the relevant areas of emerging research is investigating the role of attentional control in attentional bias (e.g. Derryberry & Reed, 2002). In this respect, according to the ACT (Eysenck et al., 2007), these bias are the result of a more general cognitive deficit which rely on the control of attention and not specifically on differential processing of the threatening information from the environment. Thus, more research remains to be done in this line in order to determine whether attentional bias in MA has to do with an overactivity of the threat-detection mechanism, underactivity of the attentional control mechanisms, or a combination of both.

MA and the brain

A network of structures including the insula, the amygdala, the anterior cingulate gyrus and the medial prefrontal cortex is important to identify the emotional significance of a stimulus, generate an affective response and regulate the affective state (Phillips, Drevets, Rauch, Lane, 2003). Regarding the amygdala, it is very well known to play a critical role in normal fear conditioning (LeDoux, 2000) and has been increasingly implicated in the pathophysiology of anxiety disorders (Rauch, Shin, & Wright, 2003). For example, amygdala hyperactivity to emotional human faces has been shown in social anxiety disorders (Birbaumer, Grodd, Diedrich, Klose, Erb, Lotze, Schneider, Weiss, & Flor, 1998; Stein, Goldin, Sareen, Zorrilla, & Brown, 2002) or post-traumatic stress disorder (Rauch, Whalen, Shin, McInerney, Macklin, Lasko, Orr, & Pitman, 2000). The relationship between anxiety and this brain structure has been extended to the field of MA by Young and colleagues (2012)'s study, in which they found that MA was associated with an hyperactivity and abnormal effective connectivity of the right amygdala.

Contrarily to the role of amygdala in anxiety, the insular cortex seems to have been neglected in human studies of anxiety (Stein, Simmons, Feinstein,& Paulus, 2007). In this sense, the insula has afferent and efferent connections to the amygdala (among other areas) (Augustine, 1996), and although it has been frequently associated with disgust (Phillips, Williams, Heining, Herba, Russell, Andrew, Bullmore, Brammer, Williams, Morgan, Young, & Gray, 2004), there is increasing evidence of a broader role of this brain structure in emotional processing (Phan, Wager, Taylor, & Liberson, 2002). Moreover, several avenues of research point to an altered insular function in several anxiety disorders. For example, symptom provocation in individuals with obsessive-compulsive disorder, simple phobia, or posttraumatic stress disorder has been shown to be associated with increased cerebral blood flow in bilateral insular cortex (Rauch, Savage, Alpert, Fischman, Jenike, 1997) and an exaggerated right insular activity has been found in response to fearful faces in individuals with specific phobia (Wright, Martis, McMullin, Shin, & Rauch, 2003). We were able to extend these findings to the field of MA, Study IV showing a greater right insular activation for numeric errors as compared to non-numeric ones for the HMA group. Nevertheless, this study was not the first one reporting insular activation in HMA individuals. Using the fMRI technique, Lyons and Beilock (2012b) reported that, when participants anticipated an upcoming math task, the greater the level of MA, the greater the activity in the bilateral dorso-posterior insula, which was interpreted as showing that the anticipation of a math task was perceived as a painful event in HMA´s brains.

To sum this up, the fact that MA activates brain areas linked to fear processing (i.e. amygdala) as well as brain areas linked to disgust and pain processing (i.e. insula), suggest that this anxiety is grounded in a visceral, aversive bodily reaction, which poses a clear mechanism that may explain the origin of negative attitudes towards mathematics and the global avoidance tendency towards math-related content in HMA individuals, constituting, thus, a contributory factor in the development and maintenance of this affective condition.

Furthermore, anxiety has also been shown to impair recruitment of prefrontal mechanisms that are critical to the active control of attention, which seems to constitute a trait characteristic that would be shown regardless of the presence or absence of threat-related stimuli (Bishop, 2009). Indeed, several types of anxious individuals show deficits across a range of non-affective tasks that place demands on attentional or cognitive control. In this respect, the substrate of the cognitive control function has been located at the DLPFC, which is considered to support the sustained representation of current goals and to facilitate task-relevant performance (MacDonald, Cohen, Stenger, & Carter, 2000). Moreover, the DLPFC is also thought to be involved in the online trial-to-trial adjustment of attentional control, which has been demonstrated through tasks such as the Stroop task, by analyzing the level of interference depending on the congruency of the previous trial (Vanderhasselt & De Raedt, 2009)

In this respect, the impaired attentional control mechanisms found for other types of anxiety (Bishop, 2009) were extended to MA by Young et al. (2012), who found that HMA individuals showed a reduced activity in the DLPFC when performing an addition and subtraction verification task (Young et al., 2012). Similarly, we found (Study III) differences between math-anxious groups in the conflict adaptation effect, that is, in the changes in cognitive control due to the congruence of the previous trial, as reflected by the CSP. Indeed, this component has been linked to the execution of top-down control (Larson et al., 2009) and its neural sources have been located, as well, in the LPFC (West, 2003). In this sense, although this thesis does not provide direct evidence of an impairment of the DLPFC in MA, Study III's results showed that one of the functions of this area (trial-to-trial adjustments of attentional control) differs between LMA and HMA individuals. Finally, and in the same line, Lyons and Beilock (2012a) found that the improvement in performance in some HMA individuals was related to a greater activation of the bilateral IFJ, an area that is co-activated with the DLPFC as part of a network associated with cognitive control (Sundermann & Pfleiderer, 2012), and thus, that plays a crucial role in this function (Derrfuss, Brass, Neumann, & von Cramon, 2005).

The construct of MA

The studies comprising this thesis support previous evidence claiming that that despite being related (r = .38; Hembree, 1990), MA and general anxiety are not the same thing and thus, that MA should be considered a separate construct. Indeed, all the evidence reported in this thesis has been obtained after controlling for the effect of trait anxiety, in order to make sure that the effects of these two variables would not be confounded.

In this respect, MA has been shown to share several cognitive and physiological aspects with other types of anxiety. For example, Study III showed a reactive recruitment of attentional control in HMA individuals as previously reported for trait anxiety. In this line, Fales et al. (2008) found, that high and low anxious individuals made strikingly different use of cognitive control brain areas (i.e. DLPFC), showing that the greater the level of trait anxiety, the more reactive the activation of the area during task performance. Similarly, Osinsky et al. (2012) found that high trait anxious individuals only exerted attentional control after incongruent trials, showing a higher processing of the task-relevant dimension of the stimulus and suppressed processing of the task-irrelevant dimension of it (i.e. suggestive of increase in cognitive control).

Moreover, several studies have found an enhanced ERN component for several anxious samples characterized by an increased sensitivity to errors (e.g. Gehring et al., 2000). In this line, Study IV also found this enhancement in the ERN component for errors committed in a numeric task but not in a non-numeric one in HMA individuals.

Furthermore, it has been suggested that attentional biases towards threatening information can be characterized as being a cognitive marker of anxiety, present in several types of anxiety disorders (Bar-Haim et al., 2007), which may provoke and maintain this affective condition (MacLeod, Rutherford, Campbell, Ebsworthy, & Holker, 2002; Mathews & MacLeod, 2002). Again, in the same line, Study V showed that attentional bias towards math-related words is present in HMA individuals, proposing this bias as a mechanism playing some role in MA development, maintenance and/or aggravation;

Finally, MA affects brain structures previously linked to other types of anxiety (e.g. Rauch et al., 2003; Wright, Martis, McMullin, Shin, & Rauch, 2003; Bishop, 2009). For example, MA is characterized by a greater activation of emotional brain areas such as the amygdala (Young et al., 2012) and the insula (Lyons & Beilock, 2012b; Study IV of this thesis), as well as by a reduced activation or reactive use of cognitive control areas such as the DLPFC (Young et al., 2012) or the IFJ (Lyons & Beilock, 2012a), respectively.

Explanations of MA

Until 2010, the main account explaining why HMA individuals show a worse math performance was the one made by Ashcraft and collaborators, which was based on Eysenck's PET (Eysenck & Calvo, 1992). According to the PET, worry or self-preoccupation thoughts consume the limited attentional resources of the central executive of WM, which are therefore less available for current task processing. Thus, adverse effects of anxiety on performance and efficiency should be greater on tasks imposing substantial demands on the processing capacity of the central executive of WM. Ashcraft and collaborators extended this explanation to the field of MA by claiming that MA would affect performance only if the task depended on substantial WM processing (i.e. only for complex arithmetic processing) and because WM resources would be devoted to the anxious reaction (i.e. worrying intrusive thoughts, ruminations, etc.) generated by the math task. Several studies supported this account of MA. For example, Ashcraft and Faust (1994) and Faust et al. (1996) reported that math-anxious groups did not differ for simple arithmetic but they did when solving complex additions, which involved more WM demanding processes such as borrowing, carrying, keeping track of intermediate results, etc. (i.e. *anxiety-complexity effect*).

Nevertheless, it has been claimed that the main theoretical assumptions of the PET lack precision and explanatory power. For example, the notion that anxiety impairs the processing efficiency of the central executive of WM is imprecise because it does not specify which central executive functions are most adversely affected by anxiety. Similarly, although several studies have shown a greater distractibility in high anxious individuals (Eysenck, 1992; Eysenck & Byrne, 1992) there is no theoretical assumption giving an explanation for these findings. In this context, the ACT (Eysenck et al., 2007) represents a major development of the previous PET, extending its scope and being more precise about the effects of anxiety on the functioning of the central executive of WM.

Thus, according to the ACT, the specific function of the central execute of WM that is affected by anxiety is attentional control, by causing an imbalance between the *stimulus-driven attentional system* (bottom-up) and the *goal-directed attentional system* (top-down), the former having more influence than the latter. Consequently, high anxious individuals would be more influenced by the *stimulus-driven attentional system*, what would make them more vulnerable to bottom-up attentional intrusions, that is, more vulnerable to distraction. The other way around, high anxious individuals would be less influenced by the *goal-directed attentional system*, which would make difficult for them to focus on the objectives of the task, increasing, again, the influence of distractors.

Among the lower level functions of the central executive of WM (i.e. inhibition, shifting and updating; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000), the inhibition function seems to be the most affected by the imbalance between the attentional systems. In this respect, while according to the PET anxiety impairs processing efficiency or performance because it produces worry, in the ACT this reason is subsumed within a broader conceptualization, according to which anxiety impairs the inhibition function: anxious individuals are more distracted by task-irrelevant stimuli whether those stimuli are external (i.e. conventional distractors) or internal (i.e. worrying thoughts, ruminations, etc.).

In this respect, previous studies on MA had shown that HMA individuals showed an inhibitory deficit when distracting information was presented; HMA individuals requiring more time for reading paragraphs with distractors embedded in the text (Hopko et al., 1998) and being slower in inhibiting attention to the distracting dimension of the stimuli in a card version of the numeric Stroop task (Hopko et al., 2002). The results of this thesis were in this line: HMA individuals showed difficulties in inhibiting attention to *large-split* solutions, devoting more time (ERP latency) and processing resources (ERP amplitude) to process this implausible solutions (Study II) and were slower in a numerical Stroop task requiring to inhibit attention to the distracting dimension of the stimuli (i.e. physical size) (Study III).

Moreover, the greater influence of the stimulus-driven attentional system in HMA individuals as compared to LMA ones can be due to the different way in which attentional control is exerted in each group. In this respect, according to the DMC account (Braver et al., 2007), low anxious individuals exert attentional control in a proactive way (i.e. sustained over time) while high anxious ones do it in a reactive way (i.e. only when needed), which leads to a greater vulnerability to distraction in the latter group. Indeed, this is what we suggested in Study III: HMA individuals, by exerting attentional control only after incongruent trials (i.e. reactive way) and not in a sustained way (i.e. proactive way; as their LMA counterparts), would have been more vulnerable to distraction.

In this line, we propose an explanation of MA in the context of the ACT (Eysenck et al., 2007), which extends and updates the main claims of the PET (Eysenck & Calvo, 1992), in which the traditional Ashcraft and collaborators' account was based. Thus, in the context of the ACT, we propose that MA is characterized by an attentional control deficit that would affect performance in tasks relying, especially, in the inhibition function. Thus, according to this view, HMA individuals will differ from their LMA counterparts when the task requires the ability to effectively maintain stimulus, goal or context information in an active state when exposed to interference, in order to effectively inhibit goal-irrelevant stimuli and/or responses.

In this line, Young et al. (2012) found evidence of a reduced activity in the DLPFC, a brain structure considered to be the substrate of the cognitive control function (MacDonald et al., 2000), which seems to support our claim of an attentional control deficit in HMA individuals.

On the other hand, there is another alternative explanation of MA, according to which MA has to do with a basic low-level deficit in numerical processing (Maloney and collaborators' account). Indeed, in a conciliatory attempt, they proposed a hybrid explanation of MA according to which HMA individuals suffer from a low level numerical deficit that would be at the base of their difficulties with more complex mathematics. These math difficulties, in turn, would result in WM-demanding ruminations and worry thoughts, which would exacerbate their initial difficulties with mathematics by the mechanisms proposed by Ashcraft and colleagues.

In this respect, this thesis supports Maloney's claim that MA affects simple arithmetic processing, and thus, against the anxiety-complexity effect. In this line, in the same way that Maloney and colleagues found differences between math-anxious groups for the simple tasks of counting objects or comparing two numbers, we found differences in an arithmetic verification task presenting implausible proposed solutions and in a single-digit numeric Stroop task.

Nevertheless, it should be mentioned that the tasks used by Maloney assessed basic numeric processing while in this thesis, Studies II and III used tasks that, although being simple, implied attentional control (i.e. resist the distracting effect of *large-split* solutions; resisting the interference of the irrelevant dimension of the numeric stimuli). As a consequence the studies comprising this thesis cannot support or challenge Maloney and collaborator's account of MA, which remains as a possible explanation of this type of anxiety.

In conclusion, this thesis proposes an explanation for MA according to which this type of anxiety affects math performance at any level of math complexity by causing an attentional control deficit in the individuals who suffer from it. This attentional control deficit would make

HMA individuals be more influenced by the effect of distracting information (bottom-up) and less able to direct their attention voluntarily towards task-relevant goals (up-down). Moreover, this attentional control deficit might be due to HMA individuals recruiting attentional control in a reactive way, that is, exerting cognitive control only when they found it is needed instead of in a sustained way. This vulnerability to distraction in HMA individuals can have important negative consequences in their learning of mathematics: they may be distracted more often during math classes, what would end up in not following the teachers' explanation; they might also be distracted when doing homework or studying for an exam, these difficulties in concentration being translated as a low level of performance; last, they might be more easily distracted by their own worrying thoughts, ruminations about math or even by math-unrelated thinking, with the correspondent consequences on math performance.

What can we do about it?

All along this thesis we have provided information about the cognitive functions that seems to be most disrupted in MA, as well as the electrophysiological correlates of some of those deficits and the brain structures underlying them. However, the latest aim of all this research on MA is to prevent young children to develop it and to alleviate its effects on those students who already suffer from it. So, taking into account all the information we have about MA: What can we do about it?

Some things teachers can do:

- Negative experiences in math classrooms have been related to the origins of MA (Bekdemir, 2010). Never be hostile or embarrass a student facing difficulties with mathematics. Do not allow other students to do it either.
- Environmental exposure to failure in math has been described as a potentially primary mechanism for MA development (Ashcraft et al., 2007). In this respect, it would be important to avoid students' frustration with mathematics by establishing progressive and feasible goals. Offer support to students in order to help them overcome their difficulties with math, make them feel comfortable when solving their doubts and encourage them to ask for help any time they need it.
- Be careful with the kind of messages given to students:

    - Consolation messages like "*It's OK, not everyone can be good at these types of problems*" (Beilock & Willingham, 2014) may send the wrong message that "*Maybe this math problem is too hard for you- given your low ability in math*" or the message "*Not everybody can be good at math*", which can be interpreted as "*You are one of those that are not good at math*".
    - It has been shown that the negative effects of MA can be transferred from HMA teachers to female students believing in certain gender stereotypes. Thus, it is important to decrease teachers´ level of mathematics anxiety in order to avoid this affective condition to be extended to her female students. In this respect, it has been suggested that MA does not come from the mathematics itself but rather from the way math is presented in school and may have been presented to school teachers when they were students (Geist, 2010).
- Try to impede the development of negative attitudes towards mathematics in HMA individuals (Hembree, 1990), given that these attitudes are linked to the avoidance of math content (Lefevre et al., 1992). Highlight the importance of mathematics, emphasize the positive qualities towards math that each student have, give positive feedback of the correctly solved tasks and minimize the importance of errors, encourage students to work hard on math as the only way of succeeding, without any special intellectual or almost "gifted" requirements.
- Identify at-risk children in order to adapt classroom requirement and specially, assessment, to them. In this respect, a single-item scale (Nuñez-Peña, Guilera, & Suárez-Pellicioni, 2013) would be advised in order to assess students' level of MA, in the case that the time limitations frequently found in classroom settings made impossible the administration of more extensive scales (e.g. sMARS). Once students with a high level of MA are detected, teachers should take into account some aspects like the fact that the effects of MA on performance have been shown to disappear when the task was performed without time pressure (Faust et al., 1996). In this respect, it has been suggested that the early use of high stress techniques like timed tests instead of more developmentally appropriate and interactive approaches lead to a high incidence of MA (Geist, 2010). In this respect, we acknowledge that a test cannot be completely time-unlimited, but our proposal is that teachers can help their HMA students' performance by sending messages like: "*Don't worry if you do not finish in an hour, I can wait for you as*

you finish” or “*Do not worry about time, you’ll have all the time you need to finish the test*”.

- Teachers should consider HMA individuals’ greater vulnerability to distraction (Hopko et al., 1998; 2002; Studies II and III of this thesis), for example, when designing math textbooks. Take into account that an excessive number of drawings or colors might have counter-productive effects on children with high levels of MA, by distracting their attention away from the math exercises.
- In the same line, it is well known that distractibility is not limited to external stimuli, but also extends to the effect of internal thinking, worrying thoughts and ruminations being able to distract the participants’ attention from the main task. In this respect, Park, Ramirez, and Beilock (2014) has shown that writing before an exam has surprising positive effects on performance. They asked students to write freely about their emotions regarding an upcoming test (for 10 min) and found that this writing helped reduce the gap between LMA and HMA students, probably because of reducing the level of worrying thinking (e.g. about the ability to perform well, about failing the exam, or the math course, etc.). This finding should also be considered as a possible class intervention that teachers can adopt in order to reduce the effects of MA on their HMA students’ math test performance.
- Study IV of this thesis showed a greater insular activation in HMA individuals for errors committed in the numeric task, which we interpreted as showing HMA individuals’ discomfort with the physiological responses elicited by a numeric error. Considering previous evidence claiming that the emotion is based on the cognitive interpretation of the internal physiological responses, it is possible that HMA individuals may have interpreted the physiological responses elicited by a numeric error as a threatening or negative event. In the field of MA, it has been suggested that a differential interpretation of the physiological responses (i.e. increase in cortisol) in LMA and HMA individuals determined their level of performance (Mattarella-Micke et al., 2011). In this respect, a curious intervention was applied by Jamieson, Mendes, Blackstock, and Schmader (2010). These researchers carried out an experiment in which they recruited students who were preparing to take the Graduate Record Examination (GRE) and made them solve a practice GRE exam in a very similar testing environment. Moreover, they collected saliva samples before and after test performance and measured the salivary alpha amylase, a measure of

the sympathetic nervous system activation. Participants were assigned to one of the two groups: a reappraisal and a control group. The reappraisal group received the following message after task instruction: "*People think that feeling anxious while taking a standardized test will make them do poorly on the test. However, recent research suggests that arousal doesn't hurt performance on these tests and can even help performance… people who feel anxious during a test might actually do better. This means that you shouldn't feel concerned if you do feel anxious while taking today's GRE test. If you find yourself feeling anxious, simply remind yourself that your arousal could be helping you do well*" (Jamieson et al., 2010, p. 6) and a control group, in which participants received no message. They found that participants at the reappraisal group exhibited a significant increase in salivary alpha amylase (considered to be showing more engagement and challenge orientation) and outperformed controls on the GRE math section both in the practice laboratory task as well as in the actual GRE. This finding suggested that appraisal has an important influence on physiology and performance. Consequently, telling the students that their physiological responses when solving a math task or test can have positive effects on performance, can help HMA individuals reduce the negative effects of their MA.

Some things psychologists can do:

- Hembree (1990)'s metanalysis showed that systematic desensitization (which aims to remove the fear response of a phobia, and substitute a relaxation response to the conditional stimulus gradually using counter-conditioning) was highly successful in reducing levels of MA (e.g. Suinn, Edie, & Spinelli, 1970). Similarly, cognitive modification to restructure faulty beliefs and build self-confidence in mathematics produced a moderate reduction in MA. On the contrary, relaxation training or group discussion seem not to be effective.
- In line with our claim that MA has to do with an attentional control deficit, this function deserves special consideration when thinking on intervention programs aiming to improve MA. In this respect, recent evidence has demonstrated that a short bout of focused breathing exercise can boost performance of students with HMA when they attempt a high-pressure arithmetic task (Brunyé, Mahoney, Giles, Rapp, Taylor, & Kanarek, 2013). According to them, that bout of focused breathing was able to train the effective control

of attention away from the distressing feelings in HMA individuals and, consequently, to focus attention on the mathematical operations.

- More concretely, given our claim that MA has to do with an attentional control deficit that would affect performance in tasks implying, specially, the inhibition function, intervention programs should be directed to train this function in HMA individuals. Indeed, that kind of training has been proven useful to reduce the level of several types of anxiety. For example, Wells (1990) developed an Attentional Training Technique to modify three conceptually distinct dimensions of attention: intensity of self-focus, attentional control and attentional breadth, which aimed to modify stable cognitive factors involved in the regulation of cognition. This procedure was shown to be effective in reducing anxiety and beliefs in negative appraisals in cases of panic and social phobia (Wells, White, & Carter, 1997).
- Finally, recently, new interventions have been developed towards decreasing the anxiety level by reducing attentional bias towards threatening information. This intervention, generally called *Attention Bias Modification Program*, is based on different modified versions of the dot probe task in order to measure and manipulate attention bias towards threatening information and has shown very promising experimental results. In this respect, it has been shown that training attention to be biased towards threat increases anxiety (MacLeod, Rutherford, Campbell, Ebsworthy, and Holker, 2002), and that training attention away from threat can actually reduce symptoms of social phobia (Amir, Weber, Beard, Bomyea, & Taylor, 2008) and generalized anxiety disorder (Schmidt, Richley, Buckner, & Timpano, 2009). This study constituted evidence supporting that attentional bias towards threat may be amenable to treatment. In this respect, training attentional bias towards math-related information in HMA individuals could be a possible way to prevent HMA individuals to intensify their levels of MA through this mechanism.

In conclusion, this thesis proposes that MA has to do with an attentional control deficit, which would be related with a reactive recruitment of attentional control and which would involve brain regions associated with emotional processing. Some ideas have been suggested regarding different ways in which the knowledge we have about MA can be applied, either by teachers or by psychologist, in order to reduce the negative impact of MA on math performance. Nevertheless, a hard work remains to be done in this respect, in order to design intervention programs aiming to train the functions most affected by MA, mainly, attentional control, inhibition and attentional bias.

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ANNEX 1: Spanish summary

Esta tesis doctoral se compone de cinco estudios cuyo objetivo era investigar las diferencias en el procesamiento numérico entre individuos con alta ansiedad a las matemáticas (AAM) y aquellos con baja ansiedad a las matemáticas (BAM) a través de medidas conductuales y de potenciales evocados cerebrales (ERPs). Esperábamos que la excelente resolución temporal de esta técnica nos permitiera obtener información más específica sobre los problemas a los que se enfrentan los individuos con AAM cuando han de procesar números.

El primer estudio pretendía adaptar al español y validar la escala sMARS (Alexander & Martray, 1989), como punto de partida de esta tesis, para asegurarnos de que el constructo de la ansiedad a las matemáticas (AM) fuera medido con un instrumento que nos proporcionara medidas válidas y fiables. La adaptación al español de esta escala dio evidencias de sus buenas propiedades psicométricas: alta consistencia interna, alta fiabilidad test-retest de 7 semanas, y alta validez convergente/discriminante.

El Estudio II pretendía investigar, con la ayuda de los ERPs, el uso de la estrategia de plausibilidad en los individuos con AAM, estudiando el hallazgo de Faust et al. (1996) en su medida de puntuaciones anómalas (*flawed scores)* para las soluciones exageradamente incorrectas (*large-split solutions*). En primer lugar, reproducimos el patrón obtenido por dichos autores. Además, el análisis de ERPs mostró que las soluciones exageradamente incorrectas generaban un componente P600/P3b de mayor amplitud y de latencia más tardía para el grupo de AAM comparado con el de BAM. Dada la funcionalidad de este componente, estos resultados sugirieron que las soluciones exageradamente incorrectas demandaron más recursos cognitivos y requirieron más tiempo para ser procesadas en el grupo de AAM que en el de BAM. Estos resultados fueron interpretados de acuerdo a la Teoría del Control Atencional (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007): los individuos con AAM, estando más influenciados por el sistema atencional ligado a estímulos (*stimulus-driven attentional system*), habrían sido más vulnerables a la distracción, y habrían sucumbido a la naturaleza distractora de las soluciones exageradamente incorrectas, empleando más recursos cognitivos y más tiempo (reflejado por la amplitud y la latencia del componente P600/P3b) para procesar esta solución implausible, en lugar de utilizar la estrategia de plausibilidad.

Por otro lado, el Estudio III consistió en investigar el correlato electrofisiológico de la interferencia numérica en individuos con AAM, por medio de una tarea de Stroop numérico. En este estudio encontramos que los individuos con AAM necesitaban más tiempo para resolver la tarea que los individuos con BAM, sugiriendo que éstos se distraían con la dimensión irrelevante de la tarea (esto es, el tamaño físico). El análisis de ERPs demostró que los individuos con AAM y BAM presentaban una adaptación al conflicto diferente: el grupo de BAM mostró una mayor amplitud del componente N450 para la interferencia precedida por congruencia respecto a la precedida por incongruencia, mientras el grupo de AAM mostró dicho aumento de amplitud, pero para el componente CSP. Estos resultados sugirieron que los grupos implementaban el control atencional de un modo diferente: de una manera proactiva por el grupo de BAM y de una manera reactiva por el grupo de AAM. Un uso reactivo del control atencional en individuos con AAM los habría hecho más influenciables por el sistema atencional ligado a estímulos y, por tanto, más vulnerables a la distracción.

Los dos estudios restantes de esta tesis doctoral pretendían explorar dos factores que podrían contribuir al desarrollo de la AM. Dado que los errores son cruciales para el aprendizaje de las matemáticas, el Estudio IV pretendía evaluar si los individuos con AAM y BAM diferirían en la manera en que procesan un error numérico respecto a otro no numérico. En este estudio encontramos que los individuos con AAM mostraron un componente ERN de mayor amplitud cuando cometían un error en la tarea numérica que cuando lo cometían en una tarea no numérica. Además el estudio con sLORETA mostró una mayor activación de la ínsula derecha para los errores cometidos en la tarea numérica respecto a la tarea no numérica, sólo para el grupo de AAM. Dado que la ínsula derecha se ha asociado al desagrado con las respuestas fisiológicas y dado que se considera que los errores generan una cascada de dichas respuestas, este hallazgo fue interpretado como indicador del malestar que los individuos con AAM habrían experimentado respecto a su respuesta fisiológica ante errores numéricos. Esta reacción corporal negativa hacia errores numéricos podría estar en la base del desarrollo de actitudes negativas hacia las matemáticas y de la tendencia de los individuos con AAM a evitar situaciones con contenido numérico.

Finalmente, el Estudio V pretendía estudiar si la ansiedad a las matemáticas podría desarrollarse a través de los mismos mecanismos por los que se ha sugerido que se desarrollarían otros tipos de ansiedad investigando, por medio de la tarea de Stroop emocional, si la AM se caracteriza por un sesgo atencional hacia información relacionada con las matemáticas. Este estudio mostró que los individuos con AAM eran más lentos en indicar el color de la tinta de palabras relacionadas con las matemáticas comparado con palabras neutras, mientras que no hubo diferencias en este sentido para el grupo de BAM. Dado que este enlentecimiento en los tiempos de respuesta en la tarea de Stroop emocional se interpreta como un sesgo atencional hacia información emocional u amenazante, este estudio demuestra que la ansiedad a las matemáticas también se caracteriza por un sesgo atencional, que podría jugar algún papel en su desarrollo, mantenimiento o empeoramiento.

Para resumir, esta tesis doctoral ha mostrado que la AM se caracteriza por una vulnerabilidad a la distracción, la cual se mostró cuando se presentó una solución exageradamente incorrecta para una tarea de sumas simples (Estudio II) y cuando el tamaño físico interfería con la magnitud numérica en una tarea de Stroop numérico (Estudio III). Además, los individuos con AAM también mostraron un uso reactivo del control atencional tras la detección del conflicto (Estudio III), mayor sensibilidad o respuesta emocional al error (Estudio IV) y un sesgo atencional hacia palabras relacionadas con las matemáticas (Estudio V).

ANNEX 2: Catalan summary

Aquesta tesi doctoral es compon de cinc estudis, l’objectiu dels quals va ser investigar les diferències en el processament numèric entre individus amb alta ansietat a les matemàtiques (AAM) i aquells amb baixa ansietat a les matemàtiques (BAM) a través de mesures comportamentals i de potencials evocats cerebrals (ERPs). Esperàvem que l'excel·lent resolució temporal d'aquesta tècnica ens permetés obtenir informació més específica sobre les dificultats a les que s'enfronten els individus amb AAM quan han de processar números.

El primer estudi pretenia adaptar a l'espanyol i validar l'escala sMARS (Alexander & Martray, 1989), com a punt de partida d'aquesta tesi, per assegurar-nos de mesurar el constructe de l'ansietat a les matemàtiques (AM) amb un instrument que ens subministrés mesures vàlides i fiables. L'adaptació a l'espanyol d'aquesta escala va donar evidències de les seves bones propietats psicomètriques: alta consistència interna, alta fiabilitat test-retest de 7 setmanes, i alta validesa convergent/discriminant.

El segon estudi pretenia investigar, amb l'ajuda dels ERPs, l'ús de l'estratègia de plausibilitat en els individus amb AAM, estudiant la troballa de Faust et al. (1996) amb la seva mesura de puntuacions anòmales (*flawed scores)* per a solucions exageradament incorrectes *(large-split solutions*). En primer lloc, vam reproduir el patró obtingut per aquests autors. A més, l'anàlisi d’ERPs va mostrar que les solucions exageradament incorrectes van generar un component P600/P3b de major amplitud i de latència més tardana al grup d’AAM comparat amb el de BAM. Donada la funcionalitat d'aquest component, aquests resultats van suggerir que les solucions exageradament incorrectes van demanar més recursos cognitius i van requerir més temps per ser processades (latència del component) en el grup de AAM que en el de BAM. Aquests resultats van ser interpretats d'acord amb la Teoria del Control Atencional (ACT; Eysenck et al., 2007): els individus amb AAM, essent més influenciats pel sistema atencional lligat a estímuls (*stimulus-driven attentional system*), haurien sigut més vulnerables a la distracció, i haurien estat més influenciats per la naturalesa distractora de les solucions exageradament incorrectes, emprant més temps i recursos cognitius per a processar aquesta solució, en lloc d'utilitzar l'estratègia de plausibilitat.

D'altra banda, l'Estudi III va consistir a investigar el correlat electrofisiològic de la interferència numèrica en individus amb AAM, per mitjà d'una tasca de Stroop numèric. En aquest estudi vam trobar que els individus amb AAM necessitaven més temps per resoldre la tasca que els individus amb BAM, suggerint que es distreien amb la dimensió irrellevant de la tasca (és a dir, la grandària física dels números). L'anàlisi d’ERPs va mostrar que els individus amb AMM i BAM van mostrar una adaptació al conflicte diferent: el grup de BAM va mostrar una major amplitud del component N450 per a la interferència precedida per congruència respecte a la precedida per incongruència, mentre el grup d'AAM va mostrar aquest augment d'amplitud, però pel component CSP. Aquests resultats van suggerir que els grups van dur a terme una implementació del control atencional diferent, la qual va ser exercida d'una manera proactiva pel grup de BAM i d'una manera reactiva pel grup de AAM. Un ús reactiu del control atencional en individus amb AAM els hauria fet més influenciables pel sistema atencional lligat a estímuls i, per tant, més vulnerables a la distracció.

Els dos estudis restants d'aquesta tesi doctoral pretenien explorar dos factors que podrien contribuir al desenvolupament de l'AM. Atès que els errors són crucials per a l'aprenentatge de les matemàtiques, l'Estudi IV pretenia avaluar si els individus amb AAM i BAM diferien en la manera en que processaven un error numèric respecte a un altre no numèric. En aquest estudi vam trobar que els individus amb AAM van mostrar un component ERN de major amplitud respecte als de BAM quan cometien un error en la tasca numèrica però no quan la tasca no era numèrica. A més l'estudi amb sLORETA va mostrar una major activació de l'ínsula dreta en els errors comesos en la tasca numèrica respecte a la tasca no numèrica, només pel grup d'AAM. Atès que l'ínsula dreta ha estat associada al desgrat causat per les respostes fisiològiques i atès que es considera que els errors generen una cascada d'aquestes respostes, aquest resultat va ser interpretat com a indicador del malestar que els individus amb AAM haurien experimentat davant errors numèrics. Aquesta reacció corporal negativa cap als errors numèrics podria estar a la base del desenvolupament d'actituds negatives cap a les matemàtiques i de la tendència dels individus amb AAM a evitar situacions amb contingut numèric.

Finalment, l'Estudi V pretenia estudiar si l'AM podria desenvolupar-se a través dels mateixos mecanismes pels quals es desenvolupen altres tipus d'ansietat, investigant, per mitjà de la tasca de Stroop emocional, si l'AM es caracteritza per un biaix atencional cap a informació relacionada amb les matemàtiques. Aquest estudi va mostrar que els individus amb AAM eren més lents en indicar el color de la tinta de paraules relacionades amb les matemàtiques comparat amb paraules neutres, mentre no van sorgir diferències en aquest sentit pel grup de BAM. Atès que aquest alentiment en els temps de resposta en la tasca de Stroop emocional s'interpreta com un biaix atencional cap a informació emocional o amenaçadora, aquest estudi demostra que l'ansietat a les matemàtiques també es caracteritza per un biaix atencional, que podria explicar el seu desenvolupament, manteniment i/o empitjorament.

En resum, aquesta tesi doctoral ha mostrat que l'AM es caracteritza per una vulnerabilitat a la distracció, la qual es va fer palesa quan es va presentar una solució exageradament incorrecta per a una tasca de sumes simples (Estudi II) i quan la grandària física interferia amb la magnitud numèrica en una tasca de Stroop numèric (Estudi III). A més, els individus amb AAM van mostrar un ús reactiu del control atencional després de la detecció del conflicte (Estudi III), una resposta emocional a l’error (Estudi IV) i un biaix atencional cap a paraules relacionades amb les matemàtiques (Estudi V).