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Role of executive functions in the relations of state- and trait-math anxiety with math performance

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Abstract

The detrimental effect of math anxiety on math performance is thought to be mediated by executive functions. Previous studies have primarily focused on trait-math anxiety rather than state-math anxiety and have typically examined a single executive function rather than comprehensively evaluating all of them. Here, we used a structural equation modeling approach to concurrently determine the potential mediating roles of different executive functions (i.e., inhibition, switching, and updating) in the relationships between both state- and trait-math anxiety and math performance. A battery of computer-based tasks and questionnaires were administered to 205 university students. Two relevant results emerged. First, confirmatory factor analysis suggests that math anxiety encompassed both trait and state dimensions and, although they share substantial variance, trait-math anxiety predicted math performance over and above state-math anxiety. Second, working memory updating was the only executive function that mediated the relationship between math anxiety and math performance; neither inhibition nor switching played mediating roles. This calls into question whether some general proposals about the relationship between anxiety and executive functions can be extended specifically to math anxiety. We also raise the possibility that working memory updating or general cognitive difficulties might precede individual differences in math anxiety.

KEYWORDS
executive functions, math anxiety, math performance, state-math anxiety, structural equation modeling, trait-math anxiety, working memory updating

INTRODUCTION

Emotions are present in students' lives and can positively or negatively influence their learning outcomes. One such emotion is math anxiety (MA), which is characterized by feelings of tension and worry in situations involving mathematics. MA almost universally is negatively related to mathematical performance.[1,2] Recent meta-analyses[3–6] converge on moderately weak negative correlations (between −0.28 and −0.34), which have remained similar for more than 30 years.[7] MA is not only related to math performance, but may also significantly impact students' academic trajectories and career decisions.[8,9] To mitigate the difficulties that individuals experience as a result of these adverse emotions, it is important to better understand the underlying mechanisms of the relationship between MA and math performance.

Trait- and state-math anxiety

Most studies have predominantly focused on trait-MA, but there is growing interest in examining state-MA (e.g., Ref. 10). Trait-MA refers to an acquired, and relatively stable, tendency to perceive situations related to math as threatening. When it is assessed, individuals must recall how they felt in some general situations in the past (e.g., taking a math test, watching a teacher work through an algebraic equation on the blackboard). This type of MA is semantic and decontextualized in the sense that it may not be related to the specific actual situation.[11] State-MA refers to a temporary anxiety response to specific math situations,[12] and its assessment takes place in the specific context of math tasks (e.g., Refs. 13–15). Thus, this type of MA is considered as context-dependent since it is aroused by the actual experiences.[11,16]

The fact that state- and trait-MA appear to be separable constructs immediately raises a question regarding their relative importance as predictors of math performance. The existing handful of studies that have measured only state-MA observed a negative relationship with math performance—similar to that reported by studies focusing on trait-MA.[16–19] However, when both types of MA were considered, a variety of results emerged. Orbach et al.[15,20] observed that only state-MA, and not trait-MA, was related to math performance. Daches Cohen et al.[12] found that trait-MA was no longer related to math performance after adjusting for state-MA. In contrast, Daker et al.[21] reported that state-MA only partially mediated the relation between trait-MA and performance. Therefore, the relative contributions of trait and state components of MA as predictors of math performance remain unclear.

Executive functions and MA

An overarching question is what is the mechanism underlying the relationship between MA and performance? A variety of factors can contribute to this relation, encompassing environmental factors, such as culture, teachers, and parents, as well as individual factors, including cognitive (e.g., working memory [WM], numerical cognition) and affective processes (for comprehensive reviews, see Refs. 22–25).

One perspective suggests that anxiety interferes with various cognitive processes necessary for numerical tasks.[25,26] Some proposals, such as the processing efficiency theory (PET),[27] posit that anxiety disrupts the functioning of WM operations. Research on WM, considered as a cognitive system with a limited capacity that can hold information temporarily,[28] has led to a substantial body of empirical evidence demonstrating that math-anxious students perform worse in WM capacity tasks than their nonanxious peers (e.g., Refs. 19, 29–32). In addition to the abundant literature showing the negative relationship between MA and WM,[5,33] there is also empirical evidence for a mediating role of WM capacity in the relationship between MA and math performance,[34–41] which was confirmed in a meta-analysis by Caviola et al.,[5] albeit with very modest estimates in terms of magnitude (but see also Ref. 42 for an example of the absence of mediation).

Attentional control theory (ACT),[43] which builds on the PET, also posits that anxiety interferes with WM, but more specifically with attentional control mechanisms supported by the central executive component of the WM model outlined by Baddeley.[44] According to ACT, anxiety impairs some key executive functions (EFs) associated with the central executive. In a seminal study, Miyake et al.[45] employed latent-variable models to identify various EFs of the central executive, revealing evidence of three basic functions: switching, inhibition, and updating. The relation between these EFs and MA is reviewed below.

Switching entails changing the focus of attention between strategies and/or responses during task performance and may be involved in math tasks as they require alternating between operations, strategies, quantities, number formats, and problem-solving steps (for reviews, see Refs. 46–49). A limited number of studies have addressed the possible association with MA, with mixed results. Thus, although some studies[20] found no relationship between MA and performance in task switching, others[50,51] observed some MA-related differences. Also, others[52] found that, among all the EFs, only shifting mediated the relationship between MA and math performance. Overall, the evidence regarding the possible mediating role of switching in the MA—math performance relationship is very limited.

Inhibition involves the suppression of dominant information and/or action tendencies that are not relevant to the goal. Inhibition is related to math performance (for reviews, see Refs. 47 and 53), since it may be involved in the suppression of inappropriate strategies, dominant numerical representations, or retrieval of overlearned outcomes (e.g., suppression of 12 when 3 + 4 appears) in math tasks. Studies exploring the relationship between inhibition and MA have produced divergent results. Several of them observed heightened interference in math-anxious individuals,[54,55] while others have reported mixed results with greater interference in high-MA individuals only under certain conditions in the Stroop[56] or flanker task[57]; still other studies failed to find individual differences related to MA in a wide range of inhibitory tasks (numerical Stroop,[58] Stroop-like,[20] Hayling,[59] inhibition naming,[52] go/no-go[60]). Thus, current research on the relationship between inhibition and MA, as well as their potential mediating role in math performance, is inconclusive.

Updating refers to the continuous monitoring, manipulation, and substitution of the information held in WM based on the task requirements. Updating is essential for retrieving partial results, maintaining relevant information, and substituting no-longer-relevant information during math tasks (for reviews, see Refs. 46, 47, 61, and 62). According to the ACT view, the impact of anxiety is expected to be less pronounced on updating than on shifting and inhibition, because updating is more related to the storage of information and is not directly linked to attentional control, unlike the other EFs.[43,63] Nonetheless, the few studies that have specifically examined updating in relation to MA have found that MA individuals may be less efficient in updating information in WM.[64,65] Therefore, evidence on updating could be seen as somewhat contradictory to the ACT's hypothesis. Further research is needed to investigate the relationship between MA and WM updating, and to compare it with other EFs.

The present study

The present study aimed to address several limitations and inconsistencies in previous research on the interplay among MA, EFs, and math performance. First, while most studies have included measures of trait MA, the role of state MA in predicting math performance has been less explored, despite theoretical proposals suggesting its relevance.[43] Given the limited research that has examined both types of MA, its relationship with math performance remains inconclusive.[12,15,20,21] Therefore, distinguishing between both types of MA and their respective relationships with math performance is particularly important and timely.

Second, as reviewed above, studies focused on a single EF suggest that updating (or WM) may mediate the relationship between MA and math performance, but the role of inhibition and switching remains unclear. The few studies that simultaneously examined various EFs have produced mixed results, with some reporting no relationship between EFs and MA,[20] while others showed that only switching played a mediating role between MA and performance.[52] Strikingly, none of these studies observed a mediating effect of WM, which is often reported when only WM is assessed.[5]

The above discrepant results may be due, in part, to the fact that prior studies often examined individual EFs using single indicators, which can lead to two major problems: task impurity and task complexity.[45,66,67] These problems can occur when a given EF is assessed with a single task; performance may reflect, in addition to the intended EF, the contribution of some other nonexecutive (e.g., verbal ability, motor speed) and executive abilities. Hence, some of the inconsistent results could be attributed to differences in the specific and common executive and nonexecutive demands imposed by each task. It is also worth noting that the EFs may not be completely independent. Indeed, Miyake et al.[45] showed that EFs were separable functions with shared commonalities, which implies that it may be difficult to isolate the specific contribution of each EF when they are assessed separately or when only one task is used to assess each EF. It could, therefore, be useful to simultaneously assess the different EFs using different indicators to determine their independent relationships with MA. On this basis, we used a structural equation modeling (SEM) approach to obtain purer measures of different EFs as well as the other constructs.

In summary, this study sought to better understand the relationship between MA and math performance by investigating the potential mediation mechanism proposed by interference theories, considering both trait- and state-MA, and comprehensively assessing different EFs using multiple indicators. Based on ACT theory,[43,68] it would be expected that inhibition and shifting are stronger mediators of the relationship between MA and math performance, with updating likely playing a relatively minor role. However, in light of the evidence reviewed above, it is conceivable that WM updating could emerge as a similarly robust mediator. In addition, it was expected that both types of MA contribute to predicting math performance although, due to the limited and inconclusive evidence accumulated, we refrain from making strong claims about their relative importance.

METHODS

Participants

A total of 205 university students participated in the present study (174 females; Mean age = 21.76 years old, SD = 3.88) for course credit. All participants gave written informed consent. The study was approved by the University of Jaén ethics committee.

Materials

Math anxiety and general anxiety

Trait-MA

The following three questionnaires were used to assess the trait component of MA.

AMAS. The Abbreviated Math Anxiety Scale (AMAS)[69,70] consists of nine items that refer to math-related situations (e.g., watching a teacher work an algebraic equation on the blackboard). Items were responded to using a 5-point Likert scale ranging from 1 (not nervous at all) to 5 (very nervous). The total score is calculated as the sum of all items. The Cronbach's α for the present study was 0.86.

sMARS. The Abbreviated Math Anxiety Rating Scale (sMARS)[71,72] includes 25 items referred to math situations (e.g., studying for a mathematics exam). Items were responded to using a 5-point Likert scale, ranging from 1 (no anxiety) to 5 (high anxiety). The total score represents the sum of the 25 items (Cronbach's $\alpha = 0.94$).

SIMA. The Single-Item Math Anxiety Scale (SIMA)[72] consists of the item: "On a scale from 1 to 10, how math anxious are you?". Reliability estimates reported in the original study ranged from 0.63 to 0.78, and the test-retest reliability statistic was $r = 0.81$.

State-MA

Four items (adapted from prior research[13,73]) were used for each of the four math tasks. After giving the corresponding instructions and in anticipation of the task, a single item was presented, which read as follows: "Indicate how nervous you feel at this moment." Items were responded to using a 5-point Likert scale ranging from 1 (not nervous at all) to 5 (very nervous). The Cronbach's α for the four items was 0.69.

General anxiety

The State-Trait Anxiety Inventory (STAI)[74] is a measure of anxiety divided into two subscales. In the present study, only the trait anxiety subscale (STAI-T) was administered as a measure of general anxiety. This scale includes 20 items that assess how frequently anxious thoughts and feelings are experienced in general. Responses are given via a 4-point Likert scale (0 = never; 1 = almost never; 2 = sometimes; 3 = often). The total score is obtained by summing the scores of all items after reversing positively worded items (range: 0–60), where higher scores indicate greater anxiety (α = 0.91).

Math performance

Math fluency

Math fluency was assessed with the corresponding subtest of the Spanish version of the Woodcock—Johnson III Tests of Achievement.[75] In this subtest, participants have to solve as many simple addition, subtraction, and multiplication problems as they can in 3 min (α = 0.97).

Number calculation

Number calculation was assessed with the calculation subtest of the Woodcock—Muñoz III Tests of Achievement.[75] In this subtest, participants have to solve as many simple arithmetical problems as they can in 4 min. For university students, we used items 3—45. The maximum number of correct answers is 42 (α = 0.78).

Word problem solving

Word problem solving was evaluated with the applied math problems subtest of the Woodcock—Muñoz Tests of Achievement.[75] Participants have to solve as many math problems as they can in 5 min. For university students, items 40—58 were used, with a maximum number of correct answers of 19 (α = 0.65).

Number series

Numerical reasoning was assessed with a modified version of the series subtest of the Differential and General Aptitude Test Battery (BADyG-M).[76] Participants were presented with 32 series of four to seven numbers, and they had to identify the number among five alternatives that continued each sequence. They had 5 min to complete this task. The maximum number of correct answers was 32 (α = 0.84).

Executive functions

Switching

The following three computerized tasks were used to assess the ability to flexibly switch between tasks. Figure 1A represents the three switching tasks used.

Symbol letter task. In this task,[77] participants had to switch between indicating the position of a symbol or a letter. They were presented with colored strings of a letter and a symbol separated by dots (e.g., #·····S; D·····%; J····· =). When the item was presented in red, participants had to indicate, as quickly as possible, the position of the letter; if it was presented in blue, they had to indicate the position of the symbol. In switching trials, the task (symbol or letter) changed from the previous trial, and in nonswitching trials, the task was the same as that in the previous trial. The dependent variable was the switching cost, calculated as the difference in average response time (RT) between the switch and nonswitch trials (α = 0.87).

Number letter task. In this task,[45,78] participants had to switch between categorizing numbers and letters. Series of pairs of letter–number items were presented in one of the four corners of the screen, one at a time (e.g., M8, A3, J9). When the item was presented in the upper half of the screen, participants had to indicate if it was odd; and when the item appeared in one of the two lower corners, they had to indicate if the letter was a vowel. There were switching trials, where the task (number or letter) changed from the previous trial, and nonswitching trials. The switching cost was calculated by subtracting the average RT on the switching trials from that on the nonswitching trials (α = 0.75).

Plus minus task. In this task,[78] participants had to switch between two simple arithmetic operations to be applied to a number. A series of colored two-digit numbers were presented in the center of the screen, one at a time. When the number appeared in red, participants had to add 2, and if the number was blue, they had to subtract 2 and enter the result using the numeric keyboard. There were switching trials, where the task (add or subtract) changed from the previous trial, and nonswitching trials. The switching cost was calculated by subtracting the average RT of the switching trials from the average RT of the nonswitching trials (α = 0.57).

Updating

The following three computerized tasks were used to assess the ability to update information in WM. Figure 1B depicts the three updating tasks used.

Arithmetical updating task. In this task,[79,80] adapted from previous research,[81,82] participants had to memorize the result of different arithmetic operations as they were presented. Lists of numbers (e.g., 25) and simple arithmetical operations (e.g., +2) were sequentially presented on the screen inside different boxes. Participants were instructed to memorize the initial number associated with each box, apply the arithmetical operations that appeared in the same box, and remember the result in order to use it in the next operation involving the same box. At the end of the list, they had to enter the last result obtained for each box. Memory load varied from 1 to 3 (i.e., 1—3 boxes). The dependent variable was the percentage of correct answers given at the end of the list (α = 0.68).

N-back task. In this task[83] adapted from previous research,[82] participants had to decide whether each item in a sequence matched the one presented *n* positions back. A series of one-digit numbers were presented sequentially in the center of the screen. Six lists were presented, two lists for each level of *n*-back (from 1-back to 3-back). Each list contained 31–33 items, with 10 targets (numbers that matched the number presented *n* positions earlier) and 20 nontargets. The depen-

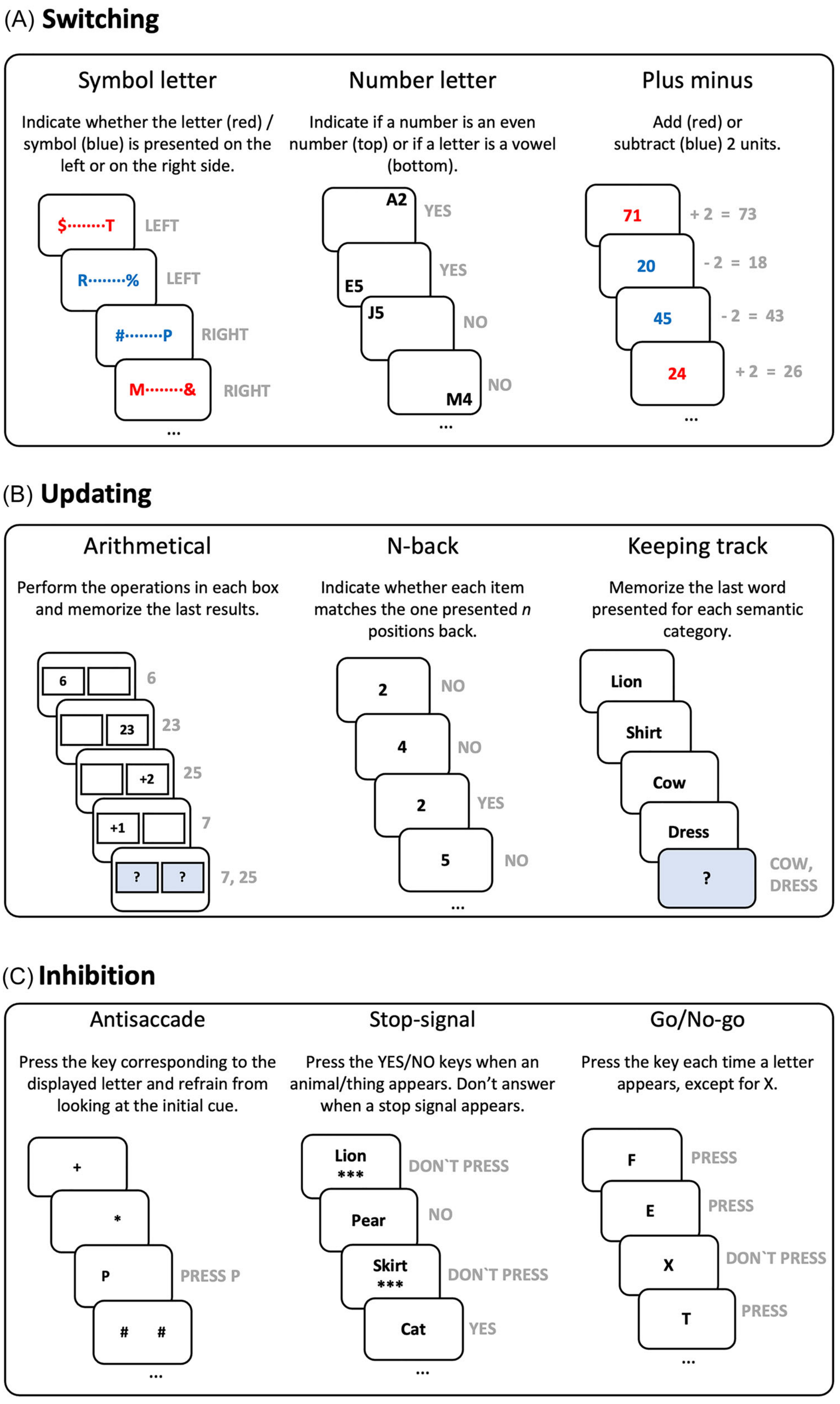

FIGURE 1 Schematic example trials for the nine executive function tasks. *Note*: Switching tasks: (A), required to switch between two tasks depending on a cue. Updating tasks (B), required to continuously substitute no-longer-relevant information in WM. Inhibition tasks (C), involved suppressing a dominant response tendency.

dent variable was a sensitivity index (*d*′) calculated by subtracting the z-score for the false alarms from the z-score for the hits (α = 0.73).

Keeping track task. In this task[84] adapted from previous research,[78] participants had to memorize the last word presented for different semantic categories. Sequences of words from different categories (animals, clothes, vegetables, furniture, and body) were presented sequentially in the center of the screen. Six lists were presented, two for each memory load level (three to five), including words from three to five categories. At the end of the list, participants had to type on the keyboard the last word presented for each category in the list. The dependent variable was the percentage of correct answers. The internal consistency of this task was very low (α = 0.43).

Inhibition

The following three tasks were used to assess the ability to inhibit a dominant response. Figure 1C represents the three inhibition tasks included.

Antisaccade task. In this task,[85] participants had to inhibit making a reflexive saccade toward a stimulus appearing in the periphery of the visual field and respond to a brief target stimulus. First, a central fixation cross ("+") appeared in the center of the screen for 500 ms. Then, a cue (an asterisk) similar to a flash (50 ms on, 25 ms off, 50 ms on) was presented on one side of the fixation cross, approximately 12.5° to the left or the right. After a short cue-to-stimulus interval (250 ms), a target (letter "P" or "Q") was displayed for 75 ms on the same or the opposite side on which the cue appeared. Finally, the target was hidden by a visual mask (#) that appeared simultaneously on both sides of the screen and remained visible until a response was made. Participants had to press the "P" or "Q" key depending on the target letter that they saw on the screen. The dependent variable was the proportion of correct responses (α = 0.96).

Stop-signal task. In this task,[45,86] participants had to categorize words except when a signal appeared indicating that they should refrain from responding. The task comprised two different blocks. In the first block (48 trials), words were sequentially presented and participants had to categorize them as either animals ("YES," "J" key) or nonanimals ("NO," "F" key) as quickly as possible without making errors. The second block included two lists totaling 128 trials, with 25% of them being stop trials. In stop trials, stop signals ("****") appeared below the word after a delay calculated by subtracting 225 ms from the average individual RT in the first block. On these trials, participants had to refrain from responding. They were encouraged not to slow down and not to wait for the stop signal to respond. The dependent variable was the proportion of categorized responses in stop trials (α = 0.90).

Go/No-go task. In this task,[86] participants had to inhibit an overlearned response when a specific stimulus was presented. Series of letters (from A to Z) were displayed in the center of the screen preceded by a fixation point (200 ms). Participants had to press "YES" when a letter was presented (Go trials), except when the letter "X" appeared, which indicated that no key had to be pressed (no-go trials). Each letter was presented for 500 ms or until a response was made. Participants were encouraged to respond as quickly as possible. Two lists of 90 trials were presented, with 20% No-go trials. Feedback for errors was given by presenting the fixation point for the next word in red font. The dependent variable was the proportion of errors in No-go trials (α = 0.81).

Procedure

All tasks were administered in small groups (maximum of 12 participants) in one session. First, participants completed questionnaires on trait-MA in the same order in which they were previously described. Subsequently, participants performed the four math performance tasks. Immediately after receiving the specific instructions for each math task and practicing with provided examples, participants were asked how nervous they were at that moment and in anticipation of similar exercises, thereby obtaining a measure of state-MA. Specifically, we asked participants, "Knowing that you are now going to do this math task, indicate how nervous you feel at this moment." Then, they performed all computerized EF tasks. Tasks tapping the same EF were presented consecutively. The most cognitively demanding tasks (updating) were administered in the middle of the session, and they were followed by a set of less demanding tasks (inhibition). This arrangement aimed to minimize the overall increase in fatigue levels by the end of the session. All questionnaires and tasks were administered in the same order in which they were described in the Materials section. The fixed order minimized potential measurement errors arising from participant-by-order interactions. All the sessions lasted up to approximately 3 h, including three short breaks.

RESULTS

Data trimming and outlier analysis

Prior to all analyses, variables were examined for outliers. For tasks with RT as the dependent variable (i.e., switching tasks), times from incorrect trials and practice lists for each participant were excluded from the analyses. Additionally, times not within three standard deviations of the mean, and RTs shorter than 250 ms, were also excluded as anticipatory responses. The proportion of trials eliminated was no more than 2.11% among the different tasks. Given that confirmatory factor analysis (CFA) and SEM are sensitive to extreme values,[87] in a second step, outliers were identified for all the variables. Values three standard deviations above or below their respective mean were substituted by the closest corresponding nonoutlier values (see Refs. 87 and 88). Less than 1.5% of the observations for any given measure were substituted by applying this trimming process. After completing this procedure, there was no evidence of deviation from normality for any of the measures (skewness < 1.82, kurtosis < 4.0).

TABLE 1 Descriptive statistics and correlations among measures.

	M	*SD*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. AMAS	25.9	6.03																					
2. sMARS	6.24	3.16	0.42**																				
3. SIMA	5.87	2.41	0.75**	0.46**																			
4. STAI-T	35.93	8.06	0.41**	0.20*	0.37**																		
5. MathFl Anx	2.61	0.94	0.49**	0.33**	0.51**	0.25**																	
6. NumCal Anx	2.94	1.03	0.53**	0.34**	0.54**	0.27**	0.73**																
7. ProbSol Anx	3.19	1.14	0.58**	0.37**	0.53**	0.33**	0.69**	0.79**															
8. NumSer Anx	3.08	1.21	0.53**	0.36**	0.46**	0.33**	0.58**	0.70**	0.79**														
9. Math Fluenc	107.33	18.44	−0.21*	−0.20*	−0.24**	−0.08	−0.18*	−0.23*	−0.23*	−0.18*													
10. Number Calc	19.07	3.96	−0.22*	−0.19*	−0.24*	−0.03	−0.17*	−0.18*	−0.19*	−0.14*	0.69**												
11. Problem Sol	5.06	2.18	−0.30**	−0.16*	−0.34**	−0.07	−0.22*	−0.23*	−0.20*	−0.18*	0.47**	0.53**											
12. Number Ser	15.44	4.79	−0.25**	−0.23*	−0.29**	−0.05	−0.24**	−0.19*	−0.17*	−0.10	0.43**	0.53**	0.59**										
13. Switch SL	−492.79	172.44	0.00	−0.12	−0.03	0.04	−0.01	−0.08	−0.04	0.04	0.08	0.05	0.14*	0.18*									
14. Switch NL	−201.28	127.97	0.03	0.01	0.01	0.13	−0.06	−0.10	−0.02	−0.01	−0.04	−0.01	0.05	0.10	0.40**								
15. Switch PM	−306.28	190.46	0.06	−0.01	0.01	0.01	−0.03	−0.06	−0.02	0.12	0.15*	0.15*	0.02	0.06	0.21*	0.18*							
16. N-back	2.71	0.53	−0.14*	−0.12	−0.14*	0.06	−0.08	−0.06	−0.04	0.03	0.18*	0.19*	0.30**	0.45**	0.30**	0.15*	0.16*						
17. Arith Updat	58.87	17.57	−0.13	−0.15*	−0.18*	0.01	−0.19*	−0.18*	−0.14*	−0.04	0.41**	0.43**	0.48**	0.51**	0.26**	0.14*	0.16*	0.28**					
18. Keep Track	61.3	11.02	0.01	0.01	−0.03	0.06	−0.01	0.04	−0.03	0.07	0.23*	0.18*	0.23*	0.29**	0.25**	0.10	0.08	0.28**	0.35**				
19. Stop-Signal	0.67	0.22	−0.03	0.11	0.05	0.02	−0.09	−0.09	−0.13	−0.13	0.00	0.02	0.05	−0.03	0.05	0.06	0.08	−0.05	0.07	0.07			
20. Go-No-go	0.7	0.16	−0.09	−0.08	−0.09	−0.09	−0.13	−0.03	−0.03	−0.05	0.06	0.04	0.09	0.11	0.04	−0.02	−0.02	0.18*	0.17*	0.07	0.15*		
21. Antisac	0.93	0.06	−0.02	−0.08	−0.05	−0.06	−0.06	−0.03	0.00	−0.01	0.10	0.16*	0.17*	0.23*	0.25**	0.15*	0.05	0.38**	0.24*	0.21*	0.12	0.23*	

Abbreviations: AMAS, Abbreviated Math Anxiety Scale; Antisac, antisaccade task; Arith Updat, arithmetical updating task; Math Fluenc, math fluency; MathFl Anx, state-MA in math fluency; N-back, N-back task; Number Calc, number calculation; Number Ser, number series; NumCal Anx, state-MA in number calculation; NumSer Anx, state-MA in number series; Problem Sol, word problem solving; ProbSol Anx, state-MA in problem solving; SIMA, Single-Item Math Anxiety Scale; sMARS, Abbreviated Math Anxiety Rating Scale; STAI-T, State-Trait Anxiety Inventory-Trait Anxiety; Switch NL, number letter switching task; Switch PM, plus minus switching task; Switch SL, symbol letter switching task.

* $p < 0.05$; ** $p < 0.001$.

Model estimation

Models were estimated with lavaan (version 0.6-13)[89] in R (version 4.2.0)[90] using mean-adjusted maximum likelihood estimation (MLM). Model fit was assessed using the following scaled indices: the Satorra–Bentler χ^2 test (χ^{2SB}), the comparative fit index (CFI), the Tucker–Lewis index (TLI), root mean square error of approximation (RMSEA), and the standardized root mean square residual (SRMR). The following conventional cutoff values indicative of adequate model fit were applied:[91] CFI and TLI greater than or equal to 0.95; RMSEA less than or equal to 0.06; and SRMR less than or equal to 0.08. Changes in model fit in the nested model comparison were tested using the Satorra–Bentler scaled χ^2 difference test[92] supplemented with the Bayesian information criterion and the Akaike information criterion.

Two measures had missing data due to participants not providing a response: MA in the number calculation task ($n = 1$) and MA in the word problem-solving task ($n = 2$). In analyses including state-MA measures, participants with missing data were excluded because the SEM estimator function (MLM), as implemented in lavaan, uses listwise deletion.

Descriptive statistics

Table 1 shows the descriptive statistics for EF, MA, and math performance measures, as well as bivariate zero-order correlations between all the measures.

Measurement models

MA models

Using CFA, four models were constructed to analyze the structural relationships between MA measures (see Table 2). Model Ma1 is a unitary model with all the indicators loading on a single factor. Model Ma2 distinguishes between trait- and state-MA. Model Ma3 is a bifactor model that includes a general MA factor and two orthogonal factors for trait- and state-MA. Model Ma4 is a variation of model Ma3 with a general factor and an orthogonal trait-MA factor. The MA models are represented in Figure S1.

All of the models exhibited a good fit, except for the one-factor model (Ma1). In particular, the bifactor model (Ma3) showed excellent fit indices (Table 2); however, all of the loadings on the orthogonal state-MA factor were very low (< 0.4) and statistically nonsignificant ($p > 0.5$), such that the validity of the model was not supported. Model Ma4 was a modification of model Ma3 in which the state-MA factor was omitted due to the nonsignificant loadings in the original model. This resulted in one general-MA factor to which all indicators loaded and one orthogonal MA-trait factor. Model Ma4 demonstrated similar fit indices to model Ma2 (see Table 2). Since model Ma2 maintains the distinction between state- and trait-MA, we selected this two-factor model as our preferred model of MA. We computed the composite reliability (*H*) of the latent variables of this model. This value was high for both state-MA ($H = 0.92$) and trait-MA ($H = 0.82$).

TABLE 2 Fit indices for confirmatory factor analyses: Comparison of math anxiety models and executive function models.

Model	χ^2(df)	CFI	TLI	RMSEA [90% CI]	SRMR	BIC	AIC
Math Anxiety (MA)							
Ma1: One-MA Factor Model	100.006 (14) **	0.878	0.817	0.194 [0.150, 0.231]	0.078	4961.225	4914.909
Ma2: Two-MS Factor Model	23.745 (13) *	0.985	0.976	0.070 [0.019, 0.114]	0.030	4870.815	4821.191
Ma3: Bifactor MA Model	6.678 (7)	1.000	1.000	0.000 [0.000, 0.087]	0.012	4881.487	4812.013
Ma4: Bifactor One Factor MA Model	21.322 (11) *	0.986	0.973	0.075 [0.023, 0.122]	0.023	4878.716	4822.476
Executive Function (EF)							
Me1: One-EF Factor Model	49.806 (27) *	0.869	0.825	0.067 [0.036, 0.095]	0.062	5148.886	5089.072
Me2: Three-EF Factor Model	22.786 (24)	1.000	1.000	0.000 [0.000, 0.055]	0.041	5135.330	5065.547
Me3: Bifactor EF Model	206.058 (25) **	0.148	−0.227	0.177 [0.155, 0.199]	0.346	5287.801	5221.340
Me4: Bifactor Two Factor EF Model	82.208 (25) **	0.686	0.547	0.107 [0.082, 0.133]	0.227	5190.609	5124.149

Abbreviations: χ^2(df), scaled chi-square test (degrees of freedom); AIC, Akaike information criterion; BIC, Bayesian information criterion; CFI, scaled comparative fit index; RMSEA, scaled root mean square error of approximation; SRMR, standardized root mean square residual; TLI, scaled Tucker–Lewis index.
* $p < 0.05$; ** $p < 0.001$.

EF models

In order to examine structural relationships between EF measures, four CFA models previously considered in the literature on EFs (see Ref. 93 for a review) were estimated (see Table 2). Model Me1 is a unitary factor model in which all indicators of EFs are related to a single factor. Model Me2 is a three-factor correlated model, the original factor structure of which was proposed by Miyake et al.,[45] which distinguishes among updating, inhibition, and switching. Model Me3 is a bifactor model including specific orthogonal factors for each of the three EFs, and a common factor in which load all the tasks. Finally, model Me4 is also a bifactor model comprising only the updating and switching orthogonal factors and a common factor that load all the tasks including the inhibition ones.[66,94] The EF models are represented in Figure S2.

Results indicated that model Me2, which represents the three correlated EF factors of updating, inhibition, and switching, exhibited a good fit to the data (see Table 2). All tasks had significant factor loadings except the stop-signal task. The other models evaluated yielded poor fit results. This finding is consistent with some prior research[45,95,96] (see also Ref. 93 for a review of the different models), demonstrating the unity and diversity of EFs. The composite reliability of the latent variables in the preferred model was poor for inhibition ($H = 0.37$), modest for updating ($H = 0.55$), and modest for switching ($H = 0.60$).

Math performance model

A model was tested in which the four indicators of math performance are related to a single factor. This unitary factor model did not provide a satisfactory fit to the data ($\chi^2(2) = 23.6$, $p < 0.001$, CFI = 0.910, TLI = 0.730, RMSEA = 0.230, 90% CI [0.155, 0.313], SRMR = 0.059). Examination of the modification indices indicated a correlated error between numeric calculation and math fluency tasks. This respecification of the model was justified as both mathematical tasks rely on the speed with which subjects can accurately perform well-learned arithmetical operations; whereas the other tasks require more complex processes such as reasoning or problem solving. The modified one-factor model provided an adequate fit to the data ($\chi^2(1) = 0.782$, $p = 0.376$, CFI = 1.0, TLI = 1.0, RMSEA = 0.0, 90% CI [0.0, 0.172], SRMR = 0.008). Standardized factor loadings ranged from 0.59 to 0.79, all significant ($ps < 0.001$). The composite reliability of the latent variable in this one-factor model was good ($H = 0.75$).

Modeling the relation between MA and EFs

Next, we examined how both types of MA (state and trait) predict the three EFs (switching, updating, and inhibition) after controlling for general anxiety, which is necessary to rule out any possible relationships being due to a nonspecific tendency toward anxiety.[97] The model fitted the data well ($\chi^2(107) = 153.35$, $p = 0.002$, CFI = 0.96, TLI = 0.94, RMSEA = 0.046, 90% CI [0.029, 0.062], SRMR = 0.074). Figure 2 shows the standardized factor loadings, latent factor correlations, and path coefficients of this model. The intercorrelations between the latent EF factors and the latent MA factors were all significant. The results further revealed that only trait-MA negatively predicted updating ($\beta = -0.38$, $p < 0.05$). However, neither trait-MA nor state-MA showed significant relations with inhibition or switching.

Modeling the relations of updating and math performance with MA

Finally, a mediation model was tested to determine the possible relationships between the two types of MA (trait and state) and math performance, and whether these relations were mediated by updating after controlling for general anxiety. In this model, only updating was included as a mediator, given that this was the only EF related to MA. The mediation model provided an acceptable fit to the data ($\chi^2(173) = 124.45$, $p = 0.001$, CFI = 0.967, TLI = 0.959, RMSEA = 0.051, 90% CI [0.032, 0.069], SRMR = 0.080). The model indicates that trait-MA had a direct effect on math performance ($c' = -0.265$, $p = 0.036$), but not state-MA ($p = 0.78$). In addition, updating partially mediated the relation between trait-MA and math performance ($a \times b = -0.247$, $p = 0.045$). Finally, the intercorrelation between both latent MA factors was significant (Figure 3). In summary, when both types of MA were considered simultaneously and general anxiety was controlled for, only

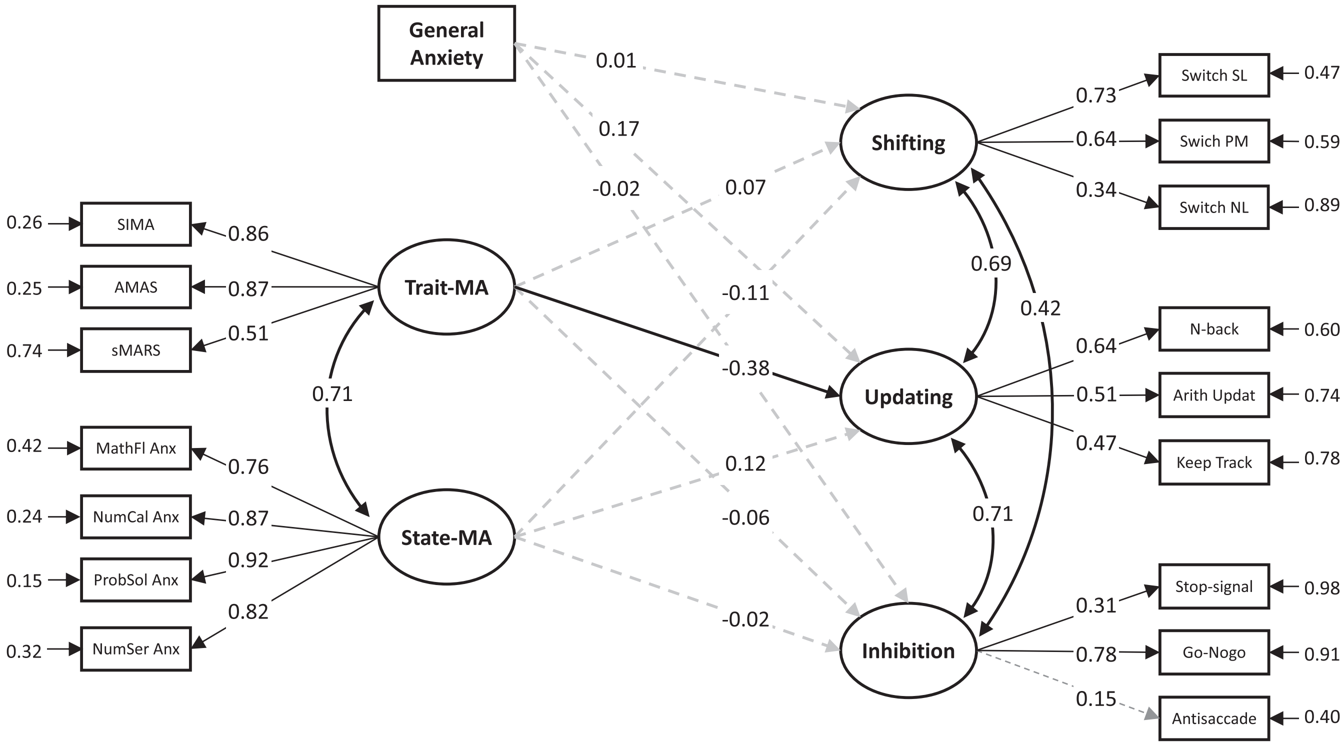

FIGURE 2 Model of the relationship between math anxiety and executive functions. *Note*: Solid lines indicate significant paths at $p < 0.05$, and dashed lines indicate nonsignificant paths ($p \geq 0.05$). Abbreviations: AMAS, Abbreviated Math Anxiety Scale; Arith Updat, arithmetical updating task; MathFl Anx, state-MA in math fluency; NumCal Anx, state-MA in number calculation; NumSer Anx, state-MA in number series; ProbSol Anx, state-MA in word problem solving; SIMA, Single-Item Math Anxiety Scale; sMARS, Abbreviated Math Anxiety Rating Scale; State-MA, state-math anxiety; Switch NL, number letter switching task; Switch PM, plus minus switching task; Switch SL, symbol letter switching task; Trait-MA, trait-math anxiety.

trait-MA was related to math performance, with updating partially mediating the relation.

Variance-partitioning analysis

To further investigate the relative importance of both types of MA (trait and state), we conducted a variance-partitioning analysis, which has previously been used to decompose the variance of cognitive measures.[98–100] The objective was to distribute the total variance explained (R^2) in math performance by MA measures into portions attributable to the shared and unique contributions of state- and trait-MA. To perform this analysis with two predictors, three regression models are needed. The variables included in these models were the latent scores derived from a CFA conducted to test the measurement model.[101]

The variance-partitioning analysis indicated that trait-MA uniquely explained 9.7% of the variance, while state-MA made a negligible unique contribution (0.2%). Additionally, both MA variables together accounted for an additional 9.6% of the variation in math performance. Therefore, all the variance accounted for by state-MA was shared variance with trait-MA.

DISCUSSION

This study aimed to comprehensively evaluate the mediating role of EF in the relationships of state- and trait-MA and math performance. By applying SEM, we found that only WM updating was related to MA; no relation was observed with inhibition or switching. Furthermore, when considering the two types of MA simultaneously, trait-MA predicted math performance independent of state-MA.

The relative importance of state- and trait-MA to math performance

Our measures allowed us to distinguish between trait- and state-MA, with the latter being far less studied than the former. To our knowledge, this is the first study to differentiate between the two types of MA using CFA. The model that included two separate but correlated factors exhibited better fit than a single-factor model and a solution with two independent factors. The preferred solution suggests that MA is a construct that includes trait and state factors with substantial shared variance. Trait-MA reflects a relatively stable disposition to experience negative affect in math situations, whereas state-MA

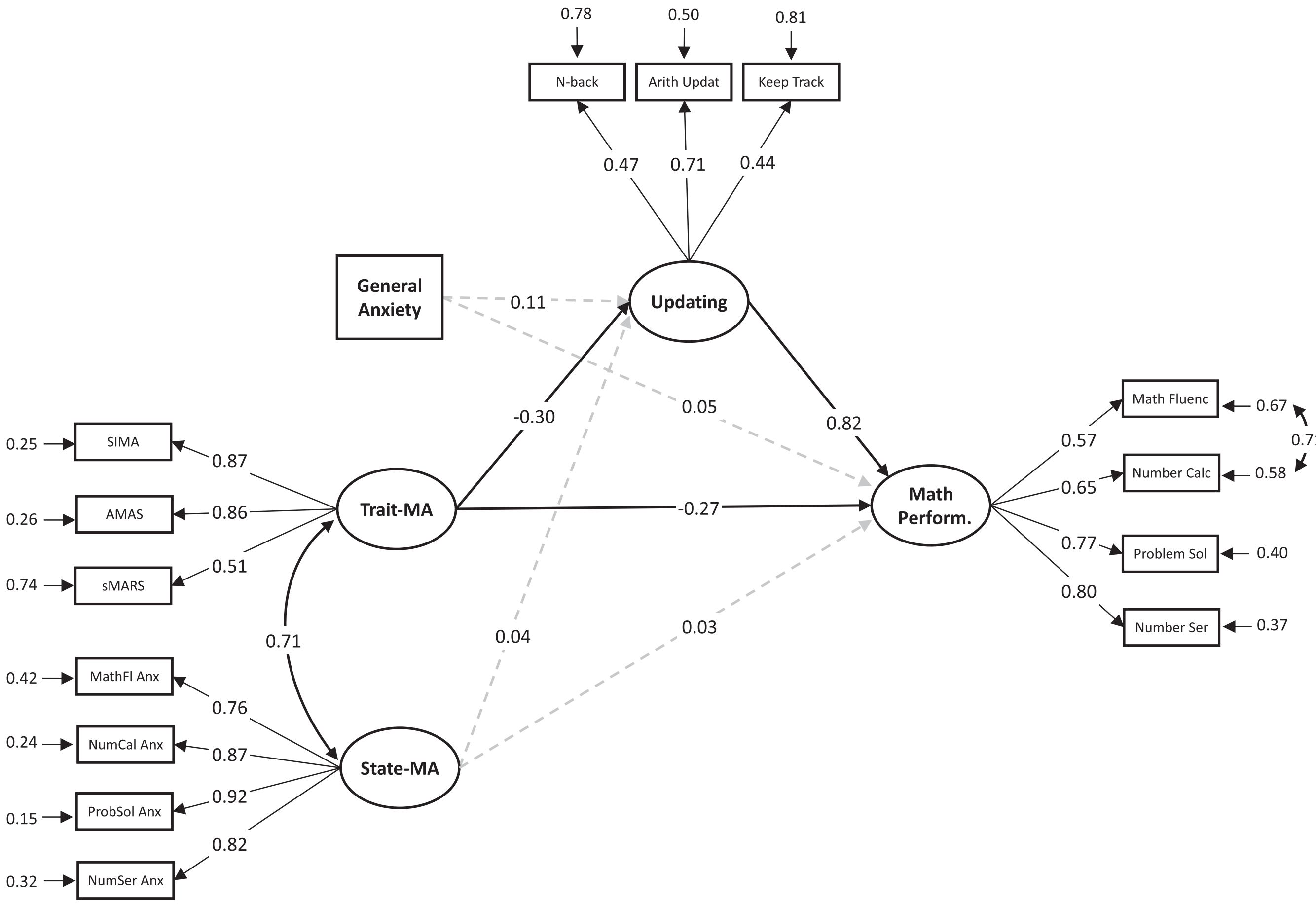

FIGURE 3 Mediation model of the relationship between math anxiety and math performance. *Note*: Solid lines indicate significant paths at $p < 0.05$, and dashed lines indicate nonsignificant paths ($p \geq 0.05$). Abbreviations: AMAS, Abbreviated Math Anxiety Scale; Arith Updat, arithmetical updating task; Math Fluenc, math fluency; MathFl Anx, state-MA in math fluency; Math Perform, math performance; Number Calc, number calculation; NumCal Anx, state-MA in number calculation; Number Ser, number series; NumSer Anx, state-MA in number series; Problem Sol, word problem solving; ProbSol Anx, state-MA in word problem solving; SIMA, the Single-Item Math Anxiety Scale; sMARS, Abbreviated Math Anxiety Rating Scale; State-MA, state-math anxiety; Trait-MA, trait-math anxiety.

reflects the intensity of emotions aroused by actual experiences and situational cues.

The strong relationship at the latent level between both types of anxiety is not surprising given that students who show high levels of trait-MA will also tend to show high levels of anxiety in specific math situations. Thus, high trait-MA students are more likely to experience state-MA of high intensity, which is consistent with correlations reported in previous research.[16] However, given that these correlations are far from perfect, it is possible that high trait-MA subjects do not show heightened state-MA in all math situations. Indeed, some previous studies have also shown different patterns of relationships for each type of MA. For example, Goetz et al.[14] found that trait-MA was related to gender, with females showing higher levels of anxiety, while state-MA during math classes was similar between boys and girls.

Both forms of MA were related to performance, but when they were entered together in the model, only trait-MA was a significant predictor. Indeed, the variance-partitioning analysis showed that trait-MA explained unique variance in math performance, whereas all the variance accounted for by state-MA was shared variance with trait-MA. This result indicates that stable and general features of MA are more predictive of math performance than state-MA, even when the latter refers to particular tasks and is measured immediately before each task is performed.

When considering the limited research that has simultaneously examined the impact of both types of MA on performance, our results are consistent with some previous data[21] showing that trait-MA was more predictive of math performance than state-MA. A similar finding has been reported in the context of statistics anxiety.[102] However, a few other studies[12,15,20] have reported that state-MA seems to play a more relevant role than trait-MA. It is possible that the more dynamic nature of state-MA in comparison to the relatively stable trait-MA may lead to different results depending on specific aspects of the evaluation setting. When a situation is perceived as important and stressful, state-MA may exhibit greater interindividual variability resulting in a stronger association with performance. Conversely, in a more neutral test situation, as in our study, state-MA may exhibit less variability and a weaker predictive relationship with math performance.

The mediating role of EFs

A main objective of this study was to determine the extent to which the different EFs mediated the relationship between MA and math performance. In contrast to most previous studies, which relied on single measures of EFs, our approach used multiple indicators to obtain purer estimates of each EF. It was found that math-anxious individuals showed lower scores in updating tasks. This result is consistent with previous research specifically focused on this EF[64,65] and is also consistent more broadly with studies using WM tasks involving a continuous requirement to update information (see Refs. 5 and 33 for reviews). Neither switching nor inhibition were related to MA, which is in line with some studies using inhibition tasks[58,60] but not with other research reporting such a relation with inhibition[55,69] or switching tasks.[50,52] It is worth noting that the best EF model in the present study consisted of three interrelated and nonindependent factors, such that updating could reflect some variance common to all EFs.[45] It is possible that some previous studies assessing single EFs detected a relationship due to common variance rather than the specific variance related to the EF targeted by the task. Overall, this finding suggests the possibility that, in studies including a single EF, the relationships between inhibition and switching with MA are conflated with aspects common to all EFs.

The present results may have implications for understanding how MA influences executive functioning. One widely accepted view is that anxiety negatively impacts math performance by causing cognitive interference. ACT[43] could be seen as a particular representation of this idea. From this perspective, in stressful situations, anxiety possibly affects inhibition and switching more so than updating.[68,103] However, the present results clearly indicated that updating, instead of switching and inhibition, mediated the relationship between MA and performance. This finding, along with those previously reviewed, calls into question whether the ACT of general anxiety can be extended to the specific case of MA in all situations. Our data fit better with other proposals that position the difficulties of anxious individuals at a broader level of WM.[104] For instance, according to PET,[27] math-anxious individuals experience intrusive thoughts and worries that deplete their limited WM resources during math tasks, ultimately hindering their performance.

Furthermore, the unique relationship between MA and WM updating suggests a second possible and nonexclusive explanation that, to our knowledge, has not received sufficient consideration within the field of MA. Specifically, it is plausible that the negative relationship with WM reflects an association between trait-MA and complex cognition. It should be borne in mind that updating is the only EF highly related to intelligence.[105,106] This explanation, which was already pointed out by Moran[104] in the context of general anxiety, is supported by some previous data. For instance, Salthouse[107] found a negative relationship between general anxiety and fluid cognition in a large sample, and in the context of MA, the meta-analysis by Hembree[7] reported a negative association between test anxiety and intelligence that has been corroborated by recent studies.[108–111]

This interpretation also fits better with the present result that trait-MA, rather than state-MA, accounts for some of the variance in EF measures. Thus, trait-MA could be a consequence of ineffective WM or certain cognitive deficits. Students who often fail to cope with certain tasks due to their somewhat limited WM may develop trait-MA as well as low math self-concept. It should be noted that trait-MA may reflect self-competence beliefs or attitudes toward mathematics.[14,112] Therefore, this could be a path through which some students (although not all; see Ref. 113) develop trait-MA. The idea of a prior deficit associated with long-term trait anxiety does not rule out the possibility that state anxiety may still interfere with WM in stressful situations.[114]

This explanation would align more closely with the deficit than with the interference (or debilitating) hypothesis regarding the origin of the relationship between MA and math performance (e.g., see Refs. 25 and 26 for overviews). In the deficit view, individuals with MA may show deficits in numerical cognition skills, as supported by previous research.[38,115,116] One possibility is that cognitive difficulties involved in the development of MA may extend beyond basic numeric skills (i.e., they may be more general). Although this idea is speculative at the moment, future studies might be able to determine whether general cognitive difficulties precede MA. Given that data collected at a single point in time cannot establish the temporal priority of one factor over another, obtaining measurements at different points in time will be necessary to determine longitudinal and concurrent associations among emotional and cognitive factors.

Limitations

The current study is not without its limitations. As noted previously, it is possible that our testing situation was not particularly stressful, and the participants probably considered the outcome of the tasks not to be especially relevant to them. Further research could shed light on this issue by inducing different levels of stress in order to increase the variability in state anxiety (e.g., Refs. 10 and 114) or using different levels of task difficulty (e.g., Ref. 117). Another potential limitation of this study was that the sample consisted mainly of women. Although women constitute a particularly relevant population in the study of MA because of their heightened levels thereof (e.g., see Refs. 7, 97, and 118), future research might benefit from a more balanced distribution of men and women.

There are some limitations related to the EF tasks used in this study, particularly regarding their relatively low composite reliabilities. While the values obtained in the present study are comparable to those found in the review by Willoughby et al.,[119] which could be attributed to the inherent nature of EFs, these low reliabilities raise concerns and warrant further attention. One potential approach to address this limitation is to increase the number of indicators (i.e., tasks) for each construct when feasible without increasing the testing burden. Another option is to select executive tasks for each construct that are expected to exhibit stronger intercorrelations.[119] This would also prevent low or nonsignificant factor loadings, as was the case in the present study for the antisaccade task in the inhibition factor (see Ref. 120 for a similar finding, also from inhibitory tasks). It is possible that differences in the response required in each inhibitory task could have contributed to this result. Whereas in the stop-signal and go/no-go tasks, participants had to refrain from giving any response in stop or go/no-go trials, in the antisaccade task, a response should be given after each trial. A selection of more representative and closely related inhibitory tasks might help to circumvent this problem.

Also, while we selected well-known tasks to assess EFs, it could be valuable to explore other types of inhibition beyond inhibition of dominant or prepotent responses. This includes resistance to proactive interference, as there is evidence suggesting potential differences among math-anxious individuals.[59] Finally, in terms of task content, our study did not control for the influence of material type on MA. Although prior meta-analyses have not found evidence that the type of material moderates the relationship between WM and MA (see the reviews by Finell et al.[33] for numerical versus non-numerical information in WM tasks and Caviola et al.[5] for visual versus verbal material), it would be interesting to explore the possible role of material type, particularly in the context of EF tasks.

CONCLUSIONS

This study found that although state- and trait-MA were both related to math performance, state-MA did not make a unique and independent contribution. Thus, trait-MA emerged as a relatively more important predictor of individual differences in math performance. Among the different EFs, only WM updating mediated the relationship between MA and performance; neither inhibition nor switching played a mediating role. These results, without ruling out the possibility that MA may interfere with cognitive functioning in stressful situations, align more with a deficit view suggesting that WM updating or general cognitive ability could be considered as an antecedent of MA. A longitudinal study is warranted to adequately evaluate this idea.

AUTHOR CONTRIBUTIONS

S.P.: Writing, study design, data analysis; M.E.M.-P.: Data analysis, revision of the manuscript; M.T.L.: Study design, revision of the manuscript; M.J.J.-G.: revision of the manuscript; R.L.: Writing, software and material development, data collection, revision of the manuscript.

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COMPETING INTERESTS

The authors have no competing interests to disclose.

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