DOI: 10.1111/nyas.14982

ORIGINAL ARTICLE

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Multidimensional components of (state) mathematics anxiety: Behavioral, cognitive, emotional, and psychophysiological consequences

Irene C. Mammarella[1] | Sara Caviola[1,2] | Serena Rossi[3] | Elisabetta Patron[4] | Daniela Palomba[4]

[1]Department of Developmental and Social Psychology, University of Padova, Padova, Italy

[2]School of Psychology, University of Leeds, Leeds, UK

[3]Centre for Mathematical Cognition, Loughborough University, Loughborough, UK

[4]Department of General Psychology, University of Padova, Padova, Italy

Correspondence
Irene C. Mammarella, Department of Developmental and Social Psychology, University of Padova, Via Venezia 8, 35131 Padova, Italy.
Email: irene.mammarella@unipd.it

Abstract

The present study aimed to analyze the different components of state mathematics anxiety that students experienced while solving calculation problems by manipulating their stress levels. A computerized mathematical task was administered to 165 fifth-graders randomly assigned to three different groups: positive, negative, and control conditions, in which positive, negative, or no feedback during the task was given, respectively. Behavioral (task performance), emotional (negative feelings), cognitive (worrisome thoughts and perceived competence), and psychophysiological responses (skin conductance and vagal withdrawal) were analyzed. Behavioral responses did not differ in the positive and negative conditions, while the latter was associated with children's reportedly negative emotional states, worries, and perceived lack of competence. The stress induced in the negative condition led to an increase in skin conductance and cardiac vagal withdrawal in children. Our data suggest the importance of considering students' interpretation of mathematics-related experiences, which might affect their emotional, cognitive, and psychophysiological responses.

KEYWORDS

arousal, autonomic response, perceived level of competence, stress manipulation

INTRODUCTION

It is generally agreed that, among the various academic subjects, mathematics involves a particularly complex interplay of cognitive and emotional processes.[1,2] Students often dread studying mathematics, not only because they worry about their academic results, but also because of the negative stress associated with it.[3] A considerable body of research has been devoted to understanding the complex interplay of responses and perspectives that contribute to describing academic anxiety, with a particular focus on mathematics anxiety (MA).[4]

However, the relationship between stress and anxiety is far from being well understood, specifically in the field of MA.[5] For math-anxious individuals, mathematics is indeed perceived as a threatening stimulus[6] and evokes feelings of tension, stress, frustration, and attentional disengagement that affect individuals' learning, leading to far-reaching consequences.[7] Thinking about mathematical learning settings, it is easy to imagine how many situations can be seen as high-stakes or stressful conditions. For example, asking somebody to perform a mathematical task under time pressure,[5] rather than providing them with overbearing or false feedback.[8,9] Overall, a stress response may be created by a real or perceived threat (stressor) and can be defined as the state of an organism in response to negative situations or conditions[10,11] that may elicit anxiety. As for anxiety, according to Leary,[12] it "refers to a cognitive-affective response characterized by physiological arousal (indicative of sympathetic nervous system activation) and apprehension regarding a potentially negative outcome that the individual perceives as impending." Thus, anxiety can be defined through different components: (1) behavioral, meaning the impulse to act or the task's performance; (2) emotional, which includes negative feelings, such as apprehension and tension;[3] (3) cognitive, which usually involve worries, task-irrelevant thoughts,[13] and negative beliefs that make individuals see themselves as inadequate in handling a particular task;[14] and finally (4) physiological changes that correspond to sympathetic nervous system activation.

Coming back to the relationship between stress and anxiety, it may change according to the presence of state or trait anxiety in an individual,[15] where the first refers to a transitory response to specific conditions, while the latter to a stable predisposition to being anxious across a variety of situations. According to Covington[16] (see also Ref. 15), high trait-anxious subjects will show greater sensitivity to evaluative stressful situations, such as those perceived in school settings where students often experience stress levels and debilitating feelings of pressure related to their performance and related evaluations. Evaluative stress leads to increased state anxiety and lower quality of performance, particularly in high trait-anxious individuals.[15] Differently, in low trait-anxious individuals, the relationship between stress and task performance may be predicted by the Yerkes–Dodson law,[17] the classical inverted-U model, according to which the optimal learning efficiency is reached with an intermediate level of stress, while performance would decline with very high (or very low) levels of stress. This prediction regards the observed *behavioral* responses, or in other words, individuals' task performance. But what happened to low trait-anxious individuals when the other components of (state) anxiety are measured (i.e., emotional, cognitive, and physiological ones)? In the present study, we aimed to study all these components related to a specific form of anxiety—namely, state MA—by testing children in an achievement-oriented situation in a school setting. It is worth noting that only a few existing studies effectively tested the multidimensionality of MA.[18] Thus, in the present study, we intentionally created a stressful situation, presenting positive/negative false feedback after children responded to mental calculations, thus eliciting their state MA. We measured not only their behavioral task performance, but also their emotional, cognitive, and psychophysiological responses associated with state-MA situations. Moreover, to reduce any possible confound, we also controlled for children's trait-MA levels.

Psychophysiological correlates of anxiety

As previously mentioned, one of the characteristics of anxiety is to induce physiological reactions that will allow the prompt detection of danger and a rapid behavioral response.[19,20] The sympathetic and parasympathetic branches of the autonomic nervous system (ANS) strictly regulate physiological arousal.[21] According to the biopsychosocial model,[22,23] the ratio of evaluated resources to demands determines whether an individual will feel challenged or threatened in goal-relevant and task-demanding situations, such as giving a speech or taking a mathematical test. From a physiological viewpoint, the experience of a challenge or threat is characterized by autonomic response patterns that include changes in both the sympathetic and parasympathetic branches of the ANS. The degree of autonomic activation influences the physiological resources available for use in building a behavioral response.[24] A challenge usually prompts a moderate sympathetic activation combined with a moderate reduction in parasympathetic activity. Such a moderate arousal associated with a challenge enables an adequate response to its demands. A threat prompts a strong sympathetic activation and can be accompanied by a marked reduction in parasympathetic activity. The high physiological arousal associated with a threat might lead to an inadequate response to the external demands it poses or to negative outcomes in the longer term.

Among the physiological measures of pure sympathetic activation, one of the least invasive and most widely used is skin conductance (SC). This is the electrodermal response caused by the activation of the sweat glands, which are innervated exclusively by the sympathetic branch of the ANS.[25] Importantly, an exaggerated SC response has been associated with a greater risk of psychopathological disorders, including anxiety[26] and depressive symptoms,[27] supporting the idea that good physiological self-regulation abilities are reflected in an adequate sympathetic response to demanding situations. Responding to a challenge can thus be expected to be associated with a moderate increase in SC, while responding to a threat would elicit a marked increase in SC.

Through the vagal nerve, the parasympathetic system acts like a brake,[24] slowing a person's heart rate. In resting conditions, parasympathetic activity on the heart (called cardiac vagal tone) ensures greater cardiac flexibility and better physiological self-regulation.[24,28,29] It has been suggested that cardiac vagal tone reflects the regulatory resources at a person's disposal for responding to external demands. In demanding situations, the parasympathetic brake is inhibited (this is also called vagal withdrawal), facilitating activation of the cardiac system and a consequent rapid adaptation, so that the body can prepare to cope with external demands.[30] Vagal withdrawal can be inferred from changes in heart rate (or a physiological variation in the interval between heartbeats), which can be reliably estimated by calculating the power spectrum in the high-frequency band of heart rate variability.[31,32]

A recent study reported that children with a moderate vagal withdrawal during a task had a better cognitive performance than children with no vagal withdrawal.[33] When faced with a demanding situation (such as a mathematical task), a moderate sympathetic activation (i.e., a moderately increased SC) associated with a moderate parasympathetic deactivation (i.e., a moderate vagal withdrawal) is likely to be associated with a better task performance (i.e., behavioral response).

Mathematics anxiety

A considerable body of research has been devoted to understanding the complex interplay of individual and contextual factors that contribute to describing academic anxiety, with a particular focus on MA.[4] Similar to other forms of anxiety, MA is multicomponent in its nature, since it involves behavioral, emotional, cognitive, and physiological manifestations.[34,35] Nevertheless, studies providing converging evidence from behavioral, cognitive-emotional, and psychophysiological data remain scarce.

Several review papers and meta-analyses[36–39] have provided up-to-date reviews of the main theoretical perspectives and have called for the future research agenda to embrace the still open questions in the field. In their opinion paper, Cipora and colleagues[18] highlighted, among others, the importance of going beyond the use of self-rating scales as the sole tool to assess MA while performing anxiety-inducing mathematics tasks, urging the inclusion of other measures (e.g., cognitive and psychophysiological). In particular, implementing other measures of MA that rely on physiological reactions may help to overcome the limitations of using only self-report data.

Previous approaches taken from the field of stress research, although limited in number, encompass the use of cortisol secretion (e.g., Refs. 40–43) and autonomic measures, such as heart rate, blood pressure, as well as SC, that seem to be associated with increased arousal during a mathematical task (e.g., Refs. 44–47). In this respect, Rozenman and colleagues[48] recently reported that young people performing a calculation task that included error-related feedback showed a pattern of autonomic activation characterized by vagal withdrawal. Similarly, Hunt and colleagues[49] found that psychophysiological responses (heart rate and blood pressure) might be modulated by task difficulty levels. Results demonstrated that a sample of primary school students was significantly affected by mental arithmetic problems of increasing difficulty, such that self-reported math anxiety was found to be significantly positively correlated with physiological reactivity—increased systolic blood pressure—to more difficult mental arithmetic.

According to Cipora et al.,[18] another important blank spot in the field of MA is represented by the state/trait discrepancy. Although the state/trait distinction is well known in the context of general anxiety,[50] only rarely is it taken into consideration in the context of MA, with a few exceptions, such as those focusing on the attentional bias (e.g., Refs. 51 and 52). Moreover, only a few studies have directly assessed state anxiety, experienced while solving mathematical problems, by means of dual-task paradigms (e.g., Ref. 53). Some other studies have instead tested state-MA levels using parallel versions of a short state (or state-like)-MA scale administered before and after a mathematical task,[54,55] or using parallel items for assessing both state and trait MA.[56]

As far as we know, no study to date has considered stress as a trigger of state MA associated with an arithmetic task, through a false feedback manipulation, by taking into account behavioral (task performance), emotional, cognitive, and physiological manifestations of MA concurrently, in children with low trait anxiety.

The present study

Assuming that it is important to consider the multifaceted expression of MA,[18] we induced situational stress conditions in fifth-graders in an effort to better understand the pattern of responses considering different MA components (i.e., behavioral, emotional, cognitive, and physiological responses). Thus, we developed an experimental design in which we intentionally created a stressful situation, by manipulating positive/negative false feedback associated with mental calculations, in order to elicit different types of reactions associated with state MA, while controlling for children's trait-MA levels. We considered fifth-grade students because most studies have investigated MA in university and secondary-school samples. Although several studies reported children as early as primary school have already experienced negative feelings toward mathematics,[2] by the age of 9–10 years old, children will have developed efficient mental calculation skills[57] and have the cognitive and metacognitive resources needed to successfully complete the various tasks we proposed.

In a group session, a sample of children was first measured on fluid intelligence, mathematical abilities, general trait anxiety, trait MA, and trait test anxiety to ensure that their baseline characteristics were comparable. In an individual session, children were assigned to one of three different experimental conditions: positive, negative, or control. To manipulate stress, we adapted the Ng and Lee paradigm:[9] The children were divided into three feedback conditions (positive, negative, and no feedback) and were given false feedback after each mental calculation trial. The positive condition corresponded to a higher proportion of positive feedback, and the negative condition to a higher proportion of negative feedback (the proportions of positive or negative feedback were established in advance); the control group received no trial-by-trial feedback. Before and after the computerized mathematical task, the children were asked to complete questionnaires on their emotional (valence, dominance, and arousal), and cognitive (perceived competence and worry) state MA. Moreover, their psychophysiological responses were recorded during the entire duration of the individual session. The children were blinded to the experimental manipulation (i.e., the trial-by-trial positive, negative, or no feedback conditions). The study thus focused on manipulating the stress levels on children's mathematical performance and observing their behavioral responses at the task level, their emotional and cognitive states, as well as their psychophysiological reactions during the task completion. In other words, we wanted to test the multidimensionality of state MA triggered by a brief exposure to perceived failure in mathematical tasks.[15,58,59]

The participants in our three (positive, negative, and control) groups had comparable levels of trait MA, trait test anxiety, and general trait anxiety, judging from the self-report questionnaires administered in the group session, enabling us to draw inferences based on our stress manipulation alone. We expected to find different behavioral, emotional, cognitive, and psychophysiological reactions reflecting distinctive responses to stress depending on each group's assigned experimental conditions, as summarized in Figure 1. We assumed that

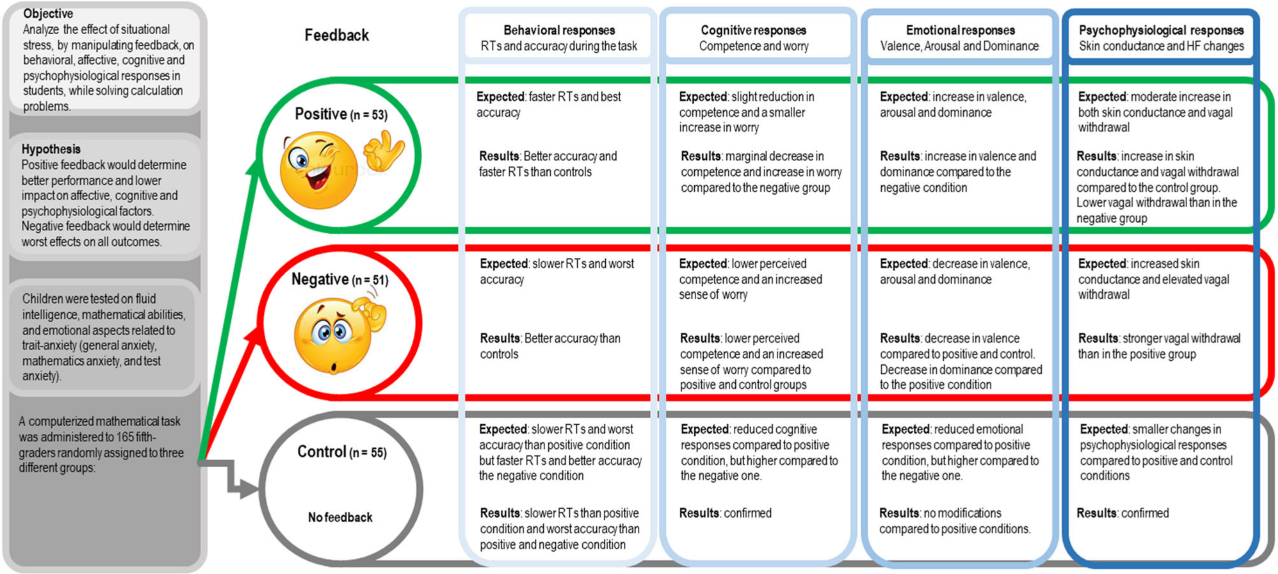

FIGURE 1 Graphical summary of the study.

the behavioral response of children in the negative condition would be worse than the one in the positive condition, but better than the one in the control group.[15]

As for emotional and cognitive responses from pre- to post-task, in the negative condition, we anticipated a lower perceived valence and dominance, a greater degree of arousal, and a lower perceived competence associated with an increased sense of worry. Conversely, children in the positive condition were expected to experience a smaller reduction in valence and sense of control/dominance, a smaller increase in arousal, and a limited loss of perceived competence, meaning a smaller increase in worry.

In terms of their psychophysiological responses, children in the negative condition were expected to have a markedly increased SC and elevated vagal withdrawal, while those in the positive condition were expected to show only a moderate increase in SC and vagal withdrawal. No clear-cut predictions were made for the children in the control group. They might, for instance, show a weaker behavioral response and physiological reactions reflecting a response to a scarcely demanding situation. If so, their physiological reactions would feature smaller changes in SC and vagal withdrawal than in either of the other conditions.

METHOD

Participants

The initial sample included 165 children, 86 girls (52.1%) and 79 boys (47.9%), with a mean age of 9.84 years ($SD = 0.39$). They were all attending state-run primary schools in northeast Italy and were from middle-class families. The study was approved by the research ethics committee at the University of Padova (Italy). Parents' written informed consent and children's verbal assent were required for participation. Children with intellectual disabilities or neurological/genetic disorders were not included in the study.

To ensure that children assigned to the experimental groups were comparable, they were tested on fluid intelligence, mathematical abilities, and emotional aspects related to trait anxiety (general anxiety, MA, and test anxiety). Fluid intelligence was measured using the Cattell Culture Fair Intelligence Test.[60] Mathematical ability was assessed using the AC-MT 6–11 battery[61] and the AC-FL,[62] which measure written and approximate calculation skills and mathematical fluency in addition and subtraction. The Revised Children's Manifest Anxiety Scale: Second Edition—Short Form (RCMAS-2)[63] was administered to assess general trait anxiety, the Abbreviated Math Anxiety Scale (AMAS)[64] for trait MA, and the Test Anxiety Questionnaire for Children (TAQ-C)[65] for trait test anxiety. The screening measures were administered in a group session lasting about 1 h.

Six children did not complete the whole assessment, so our final sample consisted of 159 children (77 boys, 48%) with: 51 ($M_{age} = 9.86$, $SD = 0.35$) in the positive condition; 53 ($M_{age} = 9.89$, $SD = 0.38$) in the negative condition; and 55 ($M_{age} = 9.76$, $SD = 0.43$) in the control condition. The three groups did not differ by: gender ($\chi^2 = 0.02$, $p = 0.91$), age ($F_{(2, 156)} = 1.38$, $p = 0.26$); fluid intelligence ($F_{(2, 156)} < 1$); mathematical abilities (mathematical fluency in additions: $F_{(2, 156)} < 1$; mathematical fluency in subtractions: $F_{(2, 156)} < 1$); approximate calculation ($F_{(2, 156)} < 1$; written calculation ($F_{(2, 156)} = 1.27$, $p = 0.29$); or trait anxiety (RCMAS: $F_{(2, 156)} = 1.03$, $p = 0.36$; AMAS: $F_{(2, 156)} < 1$; TAQ-C: $F_{(2, 156)} < 1$).

MATERIALS

Mathematical task

The computer-based mathematical task was programmed using E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA),[66] and derived from Caviola et al.[67] It was administered using a laptop computer with a 15-inch LCD screen. Children were seated in front of the screen while the experimenter sat alongside, and they were informed that they would take a computerized test that involved saying the right answer to a mathematical problem aloud as quickly and accurately as possible. Children in the positive and negative conditions were also told that feedback would appear on the screen after each problem.

The mathematical task consisted of additions or subtractions presented in the form $a + b$, where a and b were two- or three-digit numbers. Two practice problems were presented before starting the task. The mathematical task had a fixed duration of 9 min, during which children had to answer as many problems as possible. A fixation point appeared on the computer screen for 1 s, followed by a 600 ms blank interval, before each problem was presented in the middle of the screen, with three possible solutions appearing simultaneously underneath the problem. Children had to give their answer verbally, and the experimenter then pressed the corresponding button on the computer keyboard, depending on the position of the answer given by the child on the screen ("Z" for the solution on the left of the screen, "V" for the one in the middle, and "M" for the one on the right). Then, a blank screen appeared for 1 s before the next question. The problems were presented in random order. The two incorrect solutions were obtained by adding/subtracting 2 or 10 units from the correct one (counterbalanced across problems). The constraints of the problems were the same as those used in previous studies.[68,69]

Children in the positive and negative conditions saw the feedback immediately after giving their answers. The feedback was in the form of an achievement-oriented sentence, with a positive or negative valence, and feedback based on accuracy or response times (RTs) was counterbalanced in the two experimental conditions. In the positive condition, the feedback (established in advance) was positive for 75% of the solutions, and negative for 25%, simulating a situation in which the children were repeatedly right. In the negative condition, the feedback was negative for 75% of the children's answers, and positive for 25%, so the children experienced repeated failure. No trial-by-trial feedback was given to children in the no-feedback control group (see Figure 2).

Self-reports

Emotional responses

The Self-Assessment Manikin (SAM)[70] is a nonverbal, pictorial self-report scale developed to assess emotional states. In the present study, the children were presented with the SAM before and after performing the mathematical task. The SAM includes three independent affective spaces—perceived valence, arousal, and dominance/control—assessed along a 5-point visual analog scale. The SAM can be used to measure how emotional states change in response to a wide array of emotion-eliciting visual, acoustic, or textual stimuli relating to a variety of psychosocial conditions (e.g., Ref. 71). The SAM for children is a simplified 5-point pictorial valence scale where the manikin is smiling at one end and frowning at the other. The arousal scale shows a manikin sleeping at one end and jumping at the other. The dominance/control scale shows a manikin representing submission at one end and a large one representing total control at the other.[72] Specifically, the children were instructed to choose extreme pleasure on the SAM if they felt "happy, pleased, or good," and extreme displeasure if they felt "unhappy, scared, angry, bad, or sad." For arousal, they were asked to indicate the extremely calm SAM if they felt "calm, relaxed, bored, or sleepy," and the extremely aroused SAM if they felt "excited, nervous, or wide awake." For dominance, they were told to use the extreme dominance SAM if they felt "important, a leader" and the other extreme if they felt "unimportant or bullied."[72]

Cognitive responses

Before and after the computer-based mathematical task, the children were presented with two scales created ad hoc to assess their perceived levels of competence and worry about their performance in the mathematical task. The children were asked to score their feelings on a 4-point Likert scale (where 1 meant "Not at all," and 4 "Very much") before and after the mathematical task. Pre- and post-task scales were created in two parallel formats comprising 12 items. The first six items (internal consistency: pre-task Cronbach's $\alpha = 0.79$; post-task Cronbach's $\alpha = 0.87$) related to the children's perception of their own competence (e.g., pre/post-task questions: "How many answers do you think you will get/have got right in this task?"). The last six items (internal consistency; pre-task Cronbach's $\alpha = 0.75$; post-task Cronbach's $\alpha = 0.79$) concerned their sense of worry (e.g., pre-task: "Are you worried right now?"; post-task: "Were you worried while doing this task?"). Additional correlations were computed with the AMAS scores (MA) and worry questions to further assess the validity of the latter ($r_s = 0.30$ for pre- and post-task).

Electrophysiological data recording and processing

Sympathetic influence was measured in terms of SC. SC levels were recorded with two Ag/AgCl surface electrodes placed on the palmar surface of the middle phalanx of the index and middle fingers of the nondominant hand. Parasympathetic ANS influence was measured in terms of cardiac vagal control, estimated on an electrocardiogram (ECG) recorded with three Ag/AgCl surface electrodes positioned on the child's chest in a modified lead II configuration. SC and ECG were both recorded at rest for 3 min (baseline) and then during the mathematical task (9 min). Details of the electrophysiological recordings and their processing are provided in the Supplementary Material.

Procedure

Children were tested during two different sessions, both taking place at school: (1) a screening phase collectively administered in the classroom; and (2) an experimental phase, during which each child was tested individually in a quiet schoolroom. The first session was for

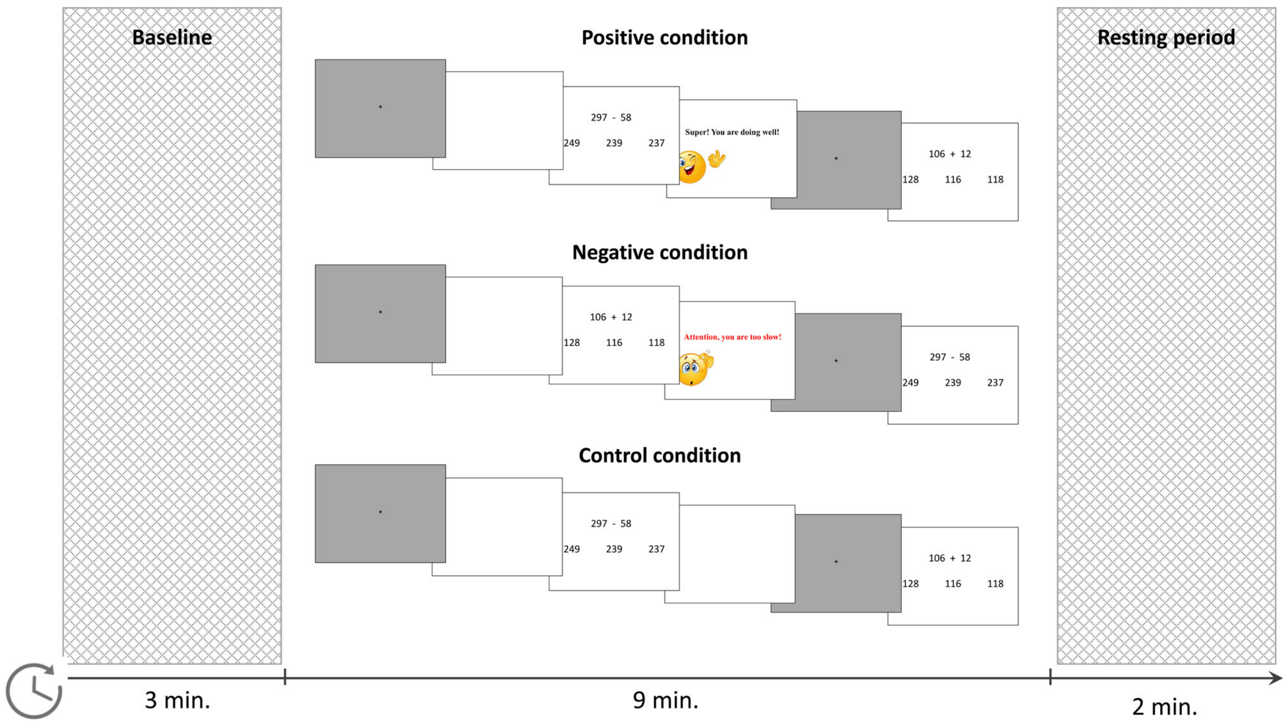

FIGURE 2 Sequence of events in the experimental phase for the three groups (positive, negative, and control conditions).

testing fluid intelligence, mathematical ability, and general, mathematics. and test trait anxiety. The second session always took place in the morning (between 9 a.m. to noon). After attaching the sensors, the researcher invited the child to sit comfortably and rest for 15 min (adaptation period). Before starting the electrophysiological recording, the child was asked to keep still to reduce movement artifacts. Then, the baseline condition was recorded at rest for 3 min. After completing the pre-task self-report scales (emotional and cognitive responses) and receiving instructions, the child was administered the 9-min mathematical task, and then asked to complete the post-task self-report scales. After a 2-min resting period, the experimenter conducted a short debriefing interview to assess the child's emotions and explain that the feedback had not always been truthful. The experimenter took care to restore positive emotions by making a great show of giving each child a certificate of participation in the study. The experimenter also asked the children if they had believed the feedback they had received, and none of them reported doubting the feedback's truthfulness. It is important to add that all the children were happy to take part in the study and joined in all the assessment sessions.

Data reduction and statistical analysis

Average RTs for correct answers and accuracy (the absolute number of correct answers) were calculated for the mathematical task. For the self-reported assessment measures (i.e., cognitive and emotional responses to the task), a differential score was calculated for each variable by subtracting the pre-task score from the post-task score (e.g., [SAM valence at post-task]—[SAM valence at pre-task]). Psychophysiological response to the task was calculated for the sympathetic and parasympathetic ANS branches. Specifically, the difference in SC level between the baseline and during the mathematical task ([SC during the mathematical task]—[baseline SC level]) reflected sympathetic activation, while the difference in high frequency (HF) power between the baseline and the first 3 min of the mathematical task ([HF power during the 4th–6th min of the procedure] – [baseline HF power during the 1st–3rd min of the procedure]) reflected parasympathetic activation.[33] This procedure was computed because parasympathetic changes are known to be fast and vagal activation occurs in less than 1 s,[73,74] while sympathetic activation is known to be slower.[75] Also, more comprehensive measures of autonomic changes might vary during the task, while vagal withdrawal was expected to peak in the first few seconds after starting to answer the questions.

A MANOVA and several one-way ANOVAs were run with Group as a between-subject factor (positive, negative, and control conditions) to examine how our experimental manipulation of the stress level influenced the children's behavioral response in the mathematical task (RTs and accuracy), and their emotional, cognitive, and psychophysiological reactions to the task (i.e., SAM for valence, arousal, and dominance; levels of competence and worry; changes in SC level and cardiac vagal withdrawal).

The partial eta-squared (η^2_p) was considered as a measure of the effect size. The η^2_p values taken to represent small, medium, and large effects are 0.01, 0.06, and 0.14, respectively.[76] Significant main effects and interactions ($p < 0.05$) were submitted to Bonferroni's post-hoc comparisons to identify specific differences. A p value < 0.05 was considered statistically significant.

TABLE 1 Descriptive statistics for RTs and accuracy in the mathematical task, pre- and post-task scores, and differential scores (Δ) in self-report measures (cognitive and emotional responses to the task), and changes in electrophysiological measures (vagal withdrawal and skin conductance) in the three groups.

		Positive condition ($n = 53$) M (SD)	Negative condition ($n = 51$) M (SD)	Control condition ($n = 55$) M (SD)
Behavioral response				
RTs (s)		9.57 (4.10)	10.08 (4.26)	11.69 (4.06)
Raw accuracy		28.60 (9.29)	27.12 (7.69)	17.60 (4.69)
Cognitive states				
Competence	PRE	15.08 (2.87)	15.06 (3.39)	14.80 (2.97)
	POST	14.85 (2.93)	12.75 (3.53)	14.58 (3.63)
	Δ	−0.23 (2.09)	−2.31 (2.40)	−0.22 (2.19)
Worry	PRE	9.70 (3.12)	10.22 (3.09)	10.51 (4.03)
	POST	10.13 (3.13)	11.86 (3.64)	11.09 (3.67)
	Δ	0.43 (1.80)	1.65 (2.26)	0.58 (2.09)
Emotional states				
SAM–Valence	PRE	4.30 (0.89)	4.37 (0.60)	4.31 (0.69)
	POST	3.74 (1.02)	3.06 (0.93)	3.67 (0.98)
	Δ	−0.57 (1.32)	−1.31 (1.07)	−0.64 (1.04)
SAM–Arousal	PRE	2.49 (1.05)	2.51 (0.76)	2.55 (1.09)
	POST	2.94 (1.05)	3.37 (0.82)	3.13 (1.11)
	Δ	0.45 (1.08)	0.86 (0.80)	0.58 (1.23)
SAM–Dominance	PRE	3.26 (0.84)	3.10 (0.61)	3.13 (0.64)
	POST	3.30 (0.85)	2.69 (0.93)	3.11 (0.66)
	Δ	0.04 (0.96)	−0.41 (1.00)	−0.02 (0.65)
Physiological measures				
*ln*HF change		−0.29 (0.54)	−0.58 (0.71)	0.02 (0.45)
*ln*SC change		0.74 (0.42)	0.61 (0.31)	0.53 (0.32)

Abbreviations: *ln*HF, logarithm of high frequency in heart rate variability; *ln*SC, logarithm of skin conductance; M, mean; RTs, response times; SD, standard deviation.

RESULTS

Table 1 shows descriptive statistics of each variable considered, by group (condition). Average RTs and accuracy in the mathematical task are reported along with pre- and post-task scores, and the differential scores obtained in the self-report questionnaires. For the physiological measures, the values show changes from the resting condition during the mathematical task for each variable in each group.

A MANOVA on behavioral response during the mathematical task showed a significant effect of stress condition on mean RT and accuracy, using Wilks's statistic, $\lambda = 0.67$, $F_{(4, 310)} = 17.35$, $p < 0.001$, $\eta^2_p = 0.183$. In particular, separate univariate ANOVAs revealed significant effects on both RTs ($F_{(2, 156)} = 3.87$, $p = 0.023$, $\eta^2_p = 0.05$) and accuracy ($F_{(2, 156)} = 34.84$, $p < 0.001$, $\eta^2_p = 0.31$). Post-hoc comparisons on RTs showed that the children in the positive condition were faster than those in the control condition ($p = 0.026$). As concerns accuracy, the children in both the positive and the negative conditions were more accurate than those in the control group (both $p_s < 0.0001$), whose accuracy scores were relatively low.

As for emotional responses to the task, the effect of stress was significant in terms of changes in SAM valence from pre- to post-task ($F_{(2, 156)} = 6.67$, $p = 0.002$; $\eta^2_p = 0.08$). Post-hoc comparisons showed that the children in the negative condition had a greater decrease in their perceived emotional valence than those in the positive ($p = 0.003$) or control ($p = 0.009$) conditions. There was no significant effect of stress on the change in SAM arousal ($F_{(2, 156)} = 2.04$, $p = 0.134$, $\eta^2_p = 0.025$). The effect of stress on the change in perceived control/dominance was significant ($F_{(2, 156)} = 4.00$, $p = 0.020$, $\eta^2_p = 0.05$). Post-hoc comparisons indicated that the children in the negative condition reported a greater decrease in their perceived control from pre- to post-task than those in the positive condition ($p = 0.031$).

Regarding cognitive responses to the task, a significant effect of stress emerged on perceived levels of competence ($F_{(2, 156)} = 15.24$, $p < 0.001$, $\eta^2_p = 0.16$), and worry ($F_{(2, 156)} = 5.35$, $p = 0.006$, $\eta^2_p = 0.06$). Post-hoc comparisons showed that children in the negative condition had a greater decline in their perceived competence than children in the positive or control conditions (both $p_s < 0.0001$), as well as a greater increase in their sense of worry compared with children in the positive ($p = 0.009$) or control ($p = 0.026$) conditions.

Finally, regarding psychophysiological responses to the mathematical task, the ANOVA on sympathetic response (as measured by the change in SC) showed a significant effect of stress ($F_{(2, 156)} = 4.89$, $p < 0.01$, $\eta^2{}_p = 0.06$). The children in the positive condition had a stronger sympathetic response than those in the control group ($p < 0.01$). No other differences emerged. The ANOVA on cardiac vagal withdrawal (as measured by the change in ln HF) showed a significant effect of stress ($F_{(2, 156)} = 14.04$, $p < 0.001$, $\eta^2{}_p = 0.15$). The children in the control condition had a weaker vagal withdrawal than those in the positive ($p = 0.02$) or negative conditions ($p < 0.001$); and the children in the negative condition had a significantly stronger vagal withdrawal than those in the positive one ($p = 0.04$).

DISCUSSION

The present study aimed to clarify the possible mechanisms involved in the relation between situational stress—experienced by students performing a mathematical task—and state-MA levels by considering their behavioral, emotional, cognitive, and psychophysiological responses. Our students were divided into three groups (positive, negative, and control condition) that were comparable in terms of trait MA and general and test trait anxiety. Our stress manipulation involved trial-by-trial feedback that did not correspond to a child's actual performance, and the students were blinded to this manipulation.

Concerning their behavioral response, children in the control condition performed significantly less well than the other two groups, suggesting that they put less effort into the mathematical task. It is worth emphasizing that the experimenter told the children in all three groups that the mathematical problems had to be solved as quickly and accurately as possible, but the children in the control group received no further information about their performance. The pattern of their psychophysiological activation suggests that this lack of feedback might have made them engage less while completing the task. Thus, concerning their behavioral responses, they were less accurate and took longer to answer than the other two groups, as the classical Yerkes–Dodson law[17] would also predict for very low levels of stress.

In line with our hypotheses, the children in the positive or negative groups gave more correct answers in the mathematical task, and the positive group worked faster than the control group. Overall, taking only the children's behavioral responses into account, we could argue that positive and negative feedback both boost performance in terms of accuracy. This finding agrees with Meijer's hypothesis,[15] according to which for low trait-anxious individuals, who presumably are much in need of achievement, the achievement-oriented stress may lead to better performance under high compared to low situational stress (see also Ref. 77). It could also be argued that the negative condition influenced our low trait-anxious children's motivation, prompting them to try harder than those in the control condition.[78,79] In their review of the literature, Mendes and Park[80] suggested, indeed, that it would be possible to maintain higher levels of arousal and still perform well if individuals could reorient their motivation from avoidance to approach states, apparently in violation of the classical Yerkes–Dodson law (see also Ref. 81).

The negative group's good behavioral response came at a price, however, and the picture changes when we look at the children's emotional, cognitive, and psychophysiological responses. Regarding the negative group's emotional responses, their choices on the SAM indicated a greater decline in their perceived emotional valence and sense of dominance/control, compared with the positive and control groups. As concerns their cognitive responses, children in the negative condition reported a greater reduction in their perceived competence after completing the mathematical task and a higher increase in their sense of worry than the other two groups. The negative group's psychophysiological responses showed a pattern of ANS activation characterized by a moderate sympathetic activation (i.e., a moderate increase in SC) and a high parasympathetic deactivation (i.e., high vagal withdrawal). In other words, although the negative group did not differ from the positive group in terms of behavioral response (mathematical task), the former children reported a pattern of negative feelings accompanied by a decline in their sense of control and perceived competence, and an increase in their sense of worry, as well as a marked vagal withdrawal.

Psychophysiological correlates of state MA

Regarding psychophysiological responses, our negative group showed a marked vagal withdrawal, reflecting a pattern of physiological arousal that could be associated with threats, and might lead in turn to an inadequate response to external demands or, in the long term, to negative outcomes such as anxiety.[82,83] A stronger vagal suppression during a mathematical task was recently found to mediate the relationship between more severe trait MA and a weaker behavioral response, suggesting a mechanism that includes both physiological and affective components behind the association between MA and performance.[84] Intriguingly, another study suggested that emotional regulation strategy training has promise as a technique for reducing negative emotional, cognitive, and psychophysiological responses to mathematical tasks, and the negative effects of MA on mathematical performance.[85]

Our positive group showed a greater sympathetic activation (i.e., a higher increase in SC during the mathematical task) than the control group, but no difference emerged between the positive and negative groups. The similar sympathetic response elicited by the mathematical task in the positive and negative groups would suggest that either type of feedback might have made the task more engaging. In line with Mendes and Park,[80] the children assigned to both experimental conditions may have shown a high level of sympathetic nervous system arousal but have been able to reorient their motivation toward an approach-oriented state, making them see the mathematical task as a challenge or exciting. Again, this could happen because our negative and positive feedback groups had comparable levels of low trait anxiety. No differences emerged, however, in the sympathetic activation of the children in the negative and control groups, suggesting that sympathetic responses alone are not enough to give a complete picture of psychophysiological activity under stress. That said, when the two measures of sympathetic and parasympathetic activation were considered, the pattern of psychophysiological activation showed that (1) the positive group had a moderate parasympathetic and high sympathetic response; (2) the negative group had the highest parasympathetic and a less marked sympathetic response; (3) and the control group showed little sympathetic activation and a blunted parasympathetic activation. The control group's more limited autonomic changes in response to the mathematical task may have failed to support these children's behavioral responses, making their RTs slower and their answers less accurate. It is worth noting that an elevated autonomic response and a blunted one may both be associated with a greater risk of behavioral and clinical issues. In fact, a small but growing body of literature indicates that both an excessive and a blunted vagal withdrawal in response to challenging situations are associated with a higher risk of developing behavioral problems,[86] impaired emotion regulation, more severe depressive symptoms over time,[87] and symptoms of anxiety.[88] The intriguing neurovisceral integration model tries to link autonomic activity with a behavioral response.[89,90] Parasympathetic activity gives an indication of the prefrontal cortex resources available for cognitive and emotional regulation,[30,90,91] so a moderate vagal withdrawal during a task is thought to reflect the active deployment of resources in the prefrontal cortex (e.g., attentional regulation) to deal with the task's cognitive demands.[91,92] The moderate and high cardiac vagal withdrawal seen in our positive and negative groups, respectively, might reflect this active deployment of prefrontal cortex resources when faced with a mathematical task, supporting the children's positive behavioral response. Further studies should test the relationship between psychophysiological activity and brain function during mathematical tasks.

The multifaceted nature of state MA

It is well known that mathematics is often associated with negative feelings,[93–95] and a huge amount of research has been done on the topic of MA (e.g., Refs. 4 and 96). A common question posed in this research field is whether MA causes poor mathematical performance, or vice versa.[1] In previous research,[58,97] the focus had mainly been on continuous exposure to failure in mathematics as a potential primary mechanism for the onset of MA (i.e., the deficit theory).[58,59] On the other hand, the deleterious anxiety model envisages children with MA as having an impaired mathematics performance because their anxiety interferes with their cognitive processes[93] (see also Ref. 3 for a review). Recent studies seem to support the hypothesis that MA could derive from exposure to adverse mathematical learning experiences in vulnerable individuals, such as those showing a tendency toward trait anxiety, who may be more at risk of developing MA.[43,98,99] Our findings seem to shed further light on the possible consequences of repeated failure in the future onset of MA. Although the children's behavioral responses were much the same in our negative and positive conditions, receiving largely negative feedback for 9 min made our participants in the negative group feel less confident and more worried about their mathematical skills. They suffered a reduction in their sense of control and perceived competence, and a heightened physiological activation. It is worth emphasizing that our three groups did not differ in terms of the trait general anxiety or MA, as measured during the screening phase (trait MA) or in the self-report measures (state MA) administered before starting the experiment. The fact that our sample was not characterized by high levels of trait MA may explain why receiving negative feedback did not affect their mathematical performance (i.e., their behavioral response).[15] However, the negative feedback did influence their emotional, cognitive, and psychophysiological responses, probably because the stress manipulation elicited a state MA. The fact that the negative group performed just as well as the positive group in the mathematical task is inconsistent with the idea that MA has a deleterious effect on mathematical performance. Our results are also not entirely in line with the deficit theory, according to which MA is elicited by experiences of poor mathematical performance.[97] In fact, the negative feedback received by our students did not correspond to their actual performance, and we found similar mathematics performance in both the positive and negative conditions.

Finally, Ramirez and colleagues[38] suggested that the onset of MA may be better explained by considering how individuals interpret (i.e., appraise) previous mathematical experiences and outcomes. According to the interpretation account theory,[38] emotional cues derive from the interpretation of events, physiological cues, personal behavior, and internal states. A recent study also suggested that not only the appraisal of previous mathematical experiences was negatively related to trait MA but also mediate the relationship between MA and mathematical attitudes.[100] Our findings seem to agree indeed with this account[38] that elicited state MA may depend on how individuals interpret their mathematics-related experiences. Our negative feedback condition seems to have prompted students to judge their performance to have been poor, with a harmful fallout on their emotional, cognitive, and physiological responses. In other words, the negative feedback made the students more likely to experience worry and negative affect, a declining sense of control and perceived competence, and greater physiological arousal. It is worth noting, however, that with our experimental manipulation, we cannot exclude the possibility of repeated exposure to failure in mathematics in real-life situations contributing to the subsequent development of trait MA.

Our negative group reported lower levels of perceived competence. According to several models, such as the expectancy-value model of achievement proposed by Eccles et al.[101,102] and the self-determination theory advanced by Deci and Ryan,[103,104] negative feedback is associated with a decline in beliefs about competence (which would presumably result in a diminished intrinsic motivation). Although we did not test students' motivation in our study, Wang et al.[105] found a negative linear correlation between trait MA and mathematical performance in less-motivated students. Future studies should, therefore, consider how different types of feedback interact with individual resources (such as motivation), and how these interactions might give rise to different profiles of academic performance, by also distinguishing between high- and low-trait MA individuals.

Our negative group also revealed a greater decrease in perceived emotional valence compared with the other groups. Emotional valence is fundamental to the classification of affective experience,[106,107] and might be the first step toward the development of a greater sensitivity to the level of danger or degree of threat in a given situation, characteristic of the typical attentional bias phenomenon seen in individuals with high levels of trait MA.[52,108]

Limitations, future directions, and implications

Although the present study offers new insight, we should mention as limitations the duration of the experimental mathematical task (which only lasted 9 min) and the fact that we only tested fifth-grade students. Further research should replicate our findings by testing younger and older students too and using longer experiments. The short-term effects seen on our negative group's emotional, cognitive, and psychophysiological responses nevertheless prompt us to recommend limiting the use of negative feedback in real classroom situations. While the children's behavioral responses (mathematical performance) did not differ between the positive and negative conditions in our experiment, after 9 min of mental calculations, we cannot infer that the situation would be the same after frequently receiving negative feedback over longer periods of time, also for children with low trait anxiety levels. It may be that receiving negative feedback repeatedly and publicly in ordinary classroom settings can have long-term consequences: students may experience more negative feelings and a greater sense of worry associated with mathematical tasks, and consequently tend to avoid mathematics-related situations. Alongside such practical implications, our study points to some areas warranting further investigation. An important aspect to strengthen the educational implications of this study is replicating our results using real feedback conditions. Our study compared negative and positive trial-by-trial feedback that did not correspond to students' actual performance. To fully implement the educational design, students should be grouped according to their prior knowledge in mathematics[109,110] and different levels of trait forms of anxiety (i.e., mathematical, test, and general anxiety). Another important set of variables future studies should include when investigating state MA is students' self-beliefs. In a previous study, Jansen and colleagues[111] controlled for the level of experienced success through an adaptive mathematical task. They found that after having experienced success, students' trait MA decreased, while the improvement of perceived mathematical competence was modest. Thus, it would be worth testing in more depth students' individual factors accompanying perceived math competence, such as self-concept and self-efficacy before and after performing calculations to gain a better understanding of the complexity of the feelings associated with the effects of stress. Moreover, further studies should also test gender-related differences on samples large enough to ensure a significant statistical power. Even though results concerning females having a higher level of MA may vary across studies depending on different cultures and age groups,[112] no study investigated what might be the causes of this discrepancy. Finally, further situational stress manipulations might be tested to improve our knowledge about state MA. For example, future studies might implement different time pressure conditions or even manipulate problem size and problem difficulties in mathematical tasks to assess how stress might diversely elicit emotional, cognitive, and psychophysiological responses of state MA (see Ref. 49).

CONCLUSIONS

To the best of our knowledge, only a few studies so far have directly assessed the multidimensional components of state MA; thus, the present study aimed to better analyze the different components of MA experienced by children while solving calculation problems under different levels of stress that may elicit state MA. Our findings highlight the need to consider behavioral responses, as well as emotional, cognitive, and psychophysiological effects when examining the issue of MA. Overall, we found that situational stress gave rise to a cost in terms of children's emotional, cognitive, and psychophysiological responses. The way students interpret the experience of failures could also increase their likelihood of developing a sense of worry and fear regarding mathematics.[98,99] According to Carey et al.,[98] trait MA can develop as a result of a student's predisposition toward general anxiety, or continuous negative experiences with mathematics, with the latter seeming to make students perform particularly badly in mathematics. If this is true, then the long-term effects of repeated failures in real-life situations, and a student's interpretation of them, might be manifested in a poor mathematical performance in the future.

To conclude, our data suggest the importance of considering behavioral, emotional, and cognitive responses, as well as psychophysiological changes when examining the issue of MA, and to take into account the disparity between state- and trait-MA levels. Overall, our behavioral data alone pointed only to superficial effects, such as an improvement in performance after perceiving repeated failures. But, under the surface of this behavioral response, there was evidence of negative feelings and a weaker sense of control, a decline in perceived competence, a greater sense of worry, and a stronger vagal withdrawal. This might suggest that early negative experiences could prompt long-term reactions.

AUTHOR CONTRIBUTIONS

I.C.M.: conceptualization, writing—original draft preparation. S.C.: writing—original draft preparation, writing—reviewing and editing. S.R.: data curation, formal analysis, writing—reviewing and editing. E.P.: data curation, formal analysis, writing—reviewing and editing. D.P.: conceptualization, writing—reviewing and editing.

ACKNOWLEDGMENTS

Open Access Funding provided by Universita degli Studi di Padova within the CRUI-CARE Agreement.

COMPETING INTERESTS

The authors declare no competing interests.

ORCID

Irene C. Mammarella https://orcid.org/0000-0002-6986-4793
Serena Rossi https://orcid.org/0000-0001-7165-5774

REFERENCES

1. Hill, F., Devine, A., & Szücs, D. (2016). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Frontiers in Psychology*, *6*, 1987.
2. Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., & Szűcs, D. (2016). Maths anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learning and Individual Differences*, *48*, 45–53.
3. Morris, L. W., Davis, M. A., & Hutchings, C. H. (1981). Cognitive and emotional components of anxiety: Literature review and a revised worry-emotional scale. *Journal of Educational Psychology*, *73*, 541–555.
4. Mammarella, I. C., Caviola, S., & Dowker, A. (2019). *Mathematics anxiety. What is known and what is still to be understood*. London: Routledge.
5. Caviola, S., Carey, E., Mammarella, I. C., & Szucs, D. (2017). Stress, time pressure, strategy selection and math anxiety in mathematics: A review of the literature. *Frontiers in Psychology*, *8*, 1–13.
6. Daches Cohen, L., & Rubinsten, O. (2022). Math anxiety and deficient executive control: Does reappraisal modulate this link? *Annals of the New York Academy of Sciences*, *1513*, 108–120.
7. Ashcraft, M. H., & Moore, A. M. (2009). Mathematics anxiety and the affective drop in performance. *Journal of Psychoeducational Assessment*, *27*, 197–205.
8. Dickerson, S. S., & Kemeny, M. E. (2004). Acute stressor and cortisol responses: A theoretical integration and synthesis of laboratory research. *Psychological Bulletin*, *130*, 355–391.
9. Ng, E., & Lee, K. (2015). Effects of trait test anxiety and state anxiety on children's working memory task performance. *Learning and Individual Differences*, *40*, 141–148.
10. Chrousos, G. P. (2009). Stress and disorders of the stress system. *Nature Reviews Endocrinology*, *5*, 374–381.
11. Endler, N. S., & Parker, J. D. A. (1990). Stress and anxiety: Conceptual and assessment issues. *Stress Medicine*, *6*, 243–248.
12. Leary, M. R. (1982). Social anxiety. In L. Wheeler (Ed.), *Review of personality and social psychology (Vol. 3)*. Beverly Hills, CA: Sage Publications.
13. Wells, A., & Matthews, G. (1994). Self-consciousness and cognitive failures as predictors of coping in stressful episodes. *Cognition and Emotion*, *8*, 279–295.
14. Lazarus, R. S. (1966). *Patterns of adjustment*. New York: McGraw Hill.
15. Meijer, J. (2001). Stress in the relation between trait and state anxiety. *Psychological Reports*, *88*, 947–964.
16. Covington, M. V. (1992). *Making the grade: A self-worth perspective on motivation and school reform*. Cambridge: Cambridge University Press.
17. Yerkes, C. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology*, *18*, 459–482.
18. Cipora, K., Santos, F. H., Kucian, K., & Dowker, A. (2022). Mathematics anxiety - Where are we and where shall we go? *Annals of the New York Academy of Sciences*, *1513*, 10–20.
19. Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion (Washington, D.C.)*, *7*, 336–353.
20. Marks, I. F., & Nesse, R. M. (1994). Fear and fitness: An evolutionary analysis of anxiety disorders. *Ethology and Sociobiology*, *15*, 247–261.
21. Kreibig, S. D., & Gendolla, G. H. E. (2014). Autonomic nervous system measurement of emotion in education and achievement setting. In R. Pekrun, & L. Linnembrink-García (Eds.), *International handbook of emotions in education* (pp. 625–642). New York: Routledge.
22. Blascovich, J., & Tomaka, J. (1996). The biopsychosocial model of arousal regulation. *Advances in Experimental Social Psychology*, *28*, 1–51.
23. Vick, S. B., Seery, M. D., Blascovich, J., & Weisbuch, M. (2008). The effect of gender stereotype activation on challenge and threat motivational states. *Journal of Experimental Social Psychology*, *44*, 624–630.
24. Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology*, *74*, 116–143.
25. Boucsein, W., Fowles, D. C., Grimnes, S., Ben-Shakhar, G., Roth, W. T., Dawson, M. E., & Filion, D. L, Society for Psychophysiological Research Ad Hoc Committee on Electrodermal Measures. (2012). Publication recommendations for electrodermal measurements. *Psychophysiology*, *49*, 1017–1034.
26. Wood, K. H., Ver Hoef, L. W., & Knight, D. C. (2014). The amygdala mediates the emotional modulation of the threat elicited skin conductance response. *Emotion (Washington, D.C.)*, *14*, 693.
27. El-Sheikh, M., & Arsiwalla, D. D. (2011). Children's sleep, skin conductance level mental health. *Journal of Sleep Research*, *20*, 326–337.
28. Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function, and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, *37*, 141–153.
29. Mccraty, R., & Shaffer, F. (2015). Heart rate variability: New perspective on physiological mechanisms, assessment of self-regulatory capacity, and health risk. *Global Advances in Health and Medicine*, *4*, 46–61.
30. Laborde, S., Mosley, E., & Mertgen, A. (2018). Vagal tank theory: The three Rs of cardiac vagal control functioning — Resting, reactivity and recovery. *Frontiers in Neuroscience*, *12*, 1–14.
31. Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology. (1996). Standards of measurement, physiological interpretation, and clinical use. *Circulation*, *93*, 1043–1065.
32. Berntson, G. G., Thomas Bigger, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & Van Der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, *34*, 623–648.
33. Scrimin, S., Patron, E., Lanfranchi, S., Moscardino, U., Palomba, D., & Mason, L. (2019). Profiles of vagal withdrawal to challenging interactions: Links with preschoolers' conceptual shifting ability. *Developmental Psychobiology*, *61*, 116–124.
34. Ashcraft, M. H. (2019). Models of math anxiety. In I. C. Mammarella, S. Caviola, & A. Dowker (Eds.), *Mathematics anxiety: What is known and what is still to be understood* (pp. 1–19). London: Routledge.
35. Rubinsten, O., Marciano, H., Eidlin Levy, H., & Daches Cohen, L. (2018). A framework for studying the heterogeneity of risk factors in math anxiety. *Frontiers in Behavioral Neuroscience*, *12*, 1–11.
36. Barroso, C., Ganley, C. M., Mcgraw, A. L., Geer, E. A., Hart, S. A., & Daucourt, M. C. (2021). A meta-analysis of the relation between math anxiety and math achievement. *Psychological Bulletin*, *147*, 134–168.

37. Caviola, S., Toffalini, E., Giofrè, D., Ruiz, J. M., Szűcs, D., & Mammarella, I. C. (2021). *Math performance and academic anxiety forms, from sociodemographic to cognitive aspects: A meta-analysis on 906,311 participants*.
38. Ramirez, G., Shaw, S. T., & Maloney, E. A. (2018). Math anxiety: Past research, promising interventions, and new interpretation framework. *Educational Psychology*, *53*, 145–164.
39. Namkung, J. M., Peng, P., & Lin, X. (2019). The relation between mathematics anxiety and mathematics performance among school-aged students: A meta-analysis. *Review of Educational Research*, *89*, 459–496.
40. Mattarella-Micke, A., Mateo, J., Kozak, M. N., Foster, K., & Beilock, S. L. (2011). Choke or thrive? The relation between salivary cortisol and math performance depends on individual differences in working memory and math-anxiety. *Emotion (Washington, D.C.)*, *11*, 1000–1005.
41. Pletzer, B., Wood, G., Moeller, K., Nuerk, H.-C., & Kerschbaum, H. H. (2010). Predictors of performance in a real-life statistics examination depend on the individual cortisol profile. *Biological Psychology*, *85*, 410–416.
42. Sarkar, A., Dowker, A., & Cohen Kadosh, R. (2014). Cognitive enhancement or cognitive cost: Trait-specific outcomes of brain stimulation in the case of mathematics anxiety. *Journal of Neuroscience*, *34*, 16605–16610.
43. Levy, H. E., & Rubinsten, O. (2021). Numbers (but no words) make math anxious individuals sweat: Psychological evidence. *Biological Psychology*, *165*, 108187.
44. Dew, K. H., Galassi, J. P., & Galassi, M. D. (1984). Math anxiety: Relation with situational test anxiety, performance, physiological arousal, and math avoidance behavior. *Journal of Counseling Psychology*, *31*, 580–583.
45. Hopko, D. R., Mcneil, D. W., Lejuez, C. W., Ashcraft, M. H., Eifert, G. H., & Riel, J. (2003). The effects of anxious responding on mental arithmetic and lexical decision task performance. *Journal of Anxiety Disorders*, *17*, 647–665.
46. Osborne, J. W. (2006). Gender, stereotype threat, and anxiety: Psychophysiological and cognitive evidence. *Electronic Journal of Research in Educational Psychology*, *4*, 109–138.
47. Salvia, E., Guillot, A., & Collet, C. (2013). The effects of mental arithmetic strain on behavioral and physiological responses. *Journal of Psychophysiology*, *27*, 173–184.
48. Rozenman, M., Sturm, A., McCracken, J. T., & Piacentini, J. (2017). Autonomic arousal in anxious and typically developing youth during a stressor involving error feedback. *European Child & Adolescent Psychiatry*, *26*, 1423–1432.
49. Hunt, T. E., Bhardwa, J., & Sheffield, D. (2017). Mental arithmetic performance, physiological reactivity and mathematics anxiety amongst U.K. primary school children. *Learning and Individual Differences*, *57*, 129–132.
50. Spielberger, C. D. (1983). *State-Trait Anxiety Inventory for Adults (STAI-AD)*. APA PsychTests.
51. Rubinsten, O., Eidlin, H., Wohl, H., & Akibli, O. (2015). Attentional bias in math anxiety. *Frontiers in Psychology*, *6*, 1539.
52. Suárez-Pellicioni, M., Núñez-Peña, M. I., & Colomé, À. (2015). Attentional bias in high math-anxious individuals: Evidence from an emotional Stroop task. *Frontiers in Psychology*, *6*, 1577.
53. Trezise, K., & Reeve, R. A. (2014). Working memory, worry, and algebraic ability. *Journal of Experimental Child Psychology*, *121*, 120–136.
54. Orbach, L., Herzog, M., & Fritz, A. (2019). Relation of state- and trait-math anxiety to intelligence, math achievement and learning motivation. *Journal of Numerical Cognition*, *5*, 371–399.
55. Orbach, L., Herzog, M., & Fritz, A. (2020). State- and trait anxiety their relation to math performance in children: The role of core executive functions. *Cognition*, *200*, 104271.
56. Roos, A.-L., Bieg, M., Goetz, T., Frenzel, A. C., Taxer, J., & Zeidner, M. (2015). Experiencing more mathematics anxiety than expected? Contrasting trait and state anxiety in high achieving students. *High Ability Studies*, *26*, 245–258.
57. Baroody, A. J., & Dowker, A. (2003). *The development of arithmetic concepts and skills*. Mahwah, NJ: Lawrence Erlbaum Associates.
58. Ashcraft, M. H., Krause, J. A., & Hopko, D. (2007). Is math anxiety a mathematical learning disability? In D. B. Berch, & M. M. M. Mazzocco (Eds.), *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities* (pp. 329–348). Baltimore, MD: Paul H Brookes Publishing Co.
59. Meece, J. L., Wigfield, A., & Eccles, J. S. (1990). Predictors of math anxiety and its influence on young adolescents' course enrollment intentions and performance in mathematics. *Journal of Educational Psychology*, *82*, 60–70.
60. Cattell, R. B., & Cattell, A. K. S. (1981). *Measuring intelligence with the culture fair tests*. Florence: Institute for Personality and Ability Testing [Misurare l'intelligenza con i test 'Culture Fair'].
61. Cornoldi, C., Lucangeli, D., & Bellina, M. (2012). *AC-MT 6–11: Test for Assessing Calculation and Problem Solving Skills [Test AC-MT 6–11 – Test di Valutazione delle Abilità di Calcolo e Problem Solving]*. Trento: Erickson.
62. Caviola, S., Gerotto, G., Lucangeli, D., & Mammarella, I. C. (2016). *Math fluency tasks [Nuove prove di fluenza per la matematica]*. Trento: Erickson.
63. Reynolds, C., & Richmond, B. (2012). *Revised Children's Manifest Anxiety Scale: Second Edition (RCMAS-2)*. Florence: Giunti OS.
64. Caviola, S., Primi, C., Chiesi, F., & Mammarella, I. C. (2017). Psychometric properties of the Abbreviated Math Anxiety Scale (AMAS) in Italian primary school children. *Learning and Individual Differences*, *55*, 174–182.
65. Donolato, E., Marci, T., Altoè, G., & Mammarella, I. C. (2019). Measuring test anxiety in primary and middle school children. Psychometric evaluation of the Test Anxiety Questionnaire for Children (TAQ-C). *Psychological Assessment*, *36*(5), 839–851.
66. Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-prime computer software and manual*. Pittsburgh, PA: Psychology Software Tools.
67. Caviola, S., Mammarella, I. C., Pastore, M., & Lefevre, J.-A. (2018). Children's strategy choices on complex subtraction problems: Individual differences and developmental changes. *Frontiers in Psychology*, *9*, 1209.
68. Caviola, S., Mammarella, I. C., Cornoldi, C., & Lucangeli, D. (2012). The involvement of working memory in children's exact and approximate mental addition. *Journal of Experimental Child Psychology*, *112*, 141–160.
69. Caviola, S., Gerotto, G., & Mammarella, I. C. (2016). Computer-based training for improving mental calculation in third- and fifth-graders. *Acta Psychologica*, *171*, 118–127.
70. Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The Self-Assessment Manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, *25*, 49–59.
71. Feldner, M. T., Zvolensky, M. J., Eifert, G. H., & Spira, A. P. (2003). Emotional avoidance: An experimental test of individual differences and response suppression using biological challenge. *Behaviour Research and Therapy*, *41*, 403–411.
72. Mcmanis, M. H., Bradley, M. M., Berg, W. K., Cuthbert, B. N., & Lang, P. J. (2001). Emotional reactions in children: Verbal, physiological, and behavioral responses to affective pictures. *Psychophysiology*, *38*, 222–231.
73. Levy, M., Martin, P., Iano, T., & Zieske, H. (1970). Effects of single vagal stimuli on heart rate and atrioventricular conduction. *American Journal of Physiology*, *218*, 1256–1262.
74. Smith, O. A. (1974). Reflex and central mechanisms involved in the control of the heart and circulation. *Annual Review of Physiology*, *36*, 93–123.
75. Warner, H. R., & Cox, A. (1962). A mathematical model of heart rate control by sympathetic and vagus efferent information. *Journal of Applied Physiology*, *17*, 349–355.

76. Cohen, J. (1977). *Statistical power analysis for the behavioral sciences*. San Diego, CA: Academic Press.
77. Sedikides, C. (1992). Mood as a determinant of attentional focus. *Cognition and Emotion*, *6*, 129–148.
78. Baumgardner, A. H. (1990). To know oneself is to like oneself: Self-certainty and self-affect. *Journal of Personality and Social Psychology*, *58*, 1062–1072.
79. Campbell, J. D. (1990). Self-esteem and clarity of the self-concept. *Journal of Personality and Social Psychology*, *59*, 538–549.
80. Mendes, W. B., & Park, J. (2014). Chapter Six–Neurobiological concomitants of motivational states. *Advances in Motivation Science*, *1*, 233–270.
81. Blascovich, J., & Mendes, W. B. (2010). Social psychophysiology and embodiment. In *Handbook of social psychology*.
82. Fortunato, C. K., Gatzke-Kopp, L. M., & Ram, N. (2013). Associations between respiratory sinus arrhythmia reactivity and internalizing and externalizing symptoms are emotion specific. *Cognitive, Affective & Behavioral Neuroscience*, *13*, 238–251.
83. Campbell, A. A., & Wisco, B. E. (2021). Respiratory sinus arrhythmia reactivity in anxiety and posttraumatic stress disorders: A review of literature. *Clinical Psychology Review*, *87*, 102034.
84. Tang, J., Su, Y., Yao, Y., Peyre, H., Guez, A., & Zhao, J. (2021). Respiratory sinus arrhythmia mediates the relation between specific math anxiety and arithmetic speed. *Frontiers in Psychology*, *12*, 135.
85. Pizzie, R. G., & Kraemer, D. J. M. (2021). The association between emotion regulation, physiological arousal, and performance in math anxiety. *Frontiers in Psychology*, *12*, 639448.
86. Calkins, S. D., Graziano, P. A., & Keane, S. P. (2007). Cardiac vagal regulation differentiates among children at risk for behavior problems. *Biological Psychology*, *74*, 144–153.
87. Gentzler, A. L., Santucci, A. K., Kovacs, M., & Fox, N. A. (2009). Respiratory sinus arrhythmia reactivity predicts emotion regulation and depressive symptoms in at-risk and control children. *Biological Psychology*, *82*, 156–163.
88. Viana, A. G., Trent, E. S., Raines, E. M., Woodward, E. C., & Zvolensky, M. J. (2019). Childhood anxiety sensitivity, fear downregulation, and anxious behaviors: Vagal suppression as a moderator of risk. *Emotion (Washington, D.C.)*, *21*(2), 430–441.
89. Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*, 201–216.
90. Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *33*, 81–88.
91. Park, G., Vasey, M. W., Van Bavel, J. J., & Thayer, J. F. (2014). When tonic cardiac vagal tone predicts changes in phasic vagal tone: The role of fear and perceptual load. *Psychophysiology*, *51*, 419–426.
92. Segerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science*, *18*, 275–281.
93. Ashcraft, M. H., & Kirk, E. P. (2001). The relationship among working memory, math anxiety and performance. *Journal of Experimental Psychology*, *130*, 224–237.
94. Maloney, E. A., & Beilock, S. L. (2012). Math anxiety: Who has it, why it develops, and how to guard against it. *Trends in Cognitive Sciences*, *16*, 404–406.
95. Vukovic, R. K., Kieffer, M. J., Bailey, S. P., & Harari, R. R. (2013). Mathematics anxiety in young children: Concurrent and longitudinal associations with mathematical performance. *Contemporary Educational Psychology*, *38*, 1–10.
96. Mammarella, I. C., Caviola, S., Giofrè, D., & Borella, E. (2018). Separating math from anxiety: The role of inhibitory mechanisms. *Applied Neuropsychology Child*, *7*, 342–353.
97. Ma, X., & Xu, J. (2004). The causal ordering of mathematics anxiety and mathematics achievement: A longitudinal panel analysis. *Journal of Adolescence*, *27*, 165–179.
98. Carey, E., Devine, A., Hill, F., & Szűcs, D. (2017). Differentiating anxiety forms and their role in academic performance from primary to secondary school. *PLoS ONE*, *12*, e0174418.
99. Mammarella, I. C., Donolato, E., Caviola, S., & Giofrè, D. (2018). Anxiety profiles and protective factors: A latent profile analysis in children. *Personality and Individual Differences*, *124*, 201–208.
100. Hunt, T. E., & Maloney, E. A. (2022). Appraisals of previous math experiences play an important role in math anxiety. *Annals of the New York Academy of Sciences*, *1515*, 143–154.
101. Eccles, J. (1983). Expectancies, values, and academic behaviors. In J.T. Spence (Ed.), *Achievement and achievement motivation : psychological and sociological approaches* (pp. 75–146). San Francisco, CA: W.H. Freeman.
102. Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, value, and goals. *Annual Review of Physiology*, *53*, 109–132.
103. Deci, E. L., & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior*. New York: Plenum.
104. Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology*, *25*, 54–67.
105. Wang, Z., Lukowski, S. L., Hart, S. A., Lyons, I. M., Thompson, L. A., Kovas, Y., Mazzocco, M. M. M., Plomin, R., & Petrill, S. A. (2015). Is math anxiety always bad for math learning? The role of math motivation. *Psychological Science*, *26*, 1863–1876.
106. Bliss-Moreau, E., Williams, L. A., & Santistevan, A. C. (2020). The immutability of valence and arousal in the foundation of emotion. *Emotion (Washington, D.C.)*, *20*, 993–1004.
107. Kuppens, P., Tuerlinckx, F., Russell, J. A., & Barrett, L. F. (2013). The relation between valence and arousal in subjective experience. *Psychological Bulletin*, *139*, 917–940.
108. Pizzie, R. G., & Kraemer, D. J. M. (2017). Avoiding math on a rapid timescale: Emotional responsivity and anxious attention in math anxiety. *Brain and Cognition*, *118*, 100–107.
109. Fyfe, E. R., Rittle-Johnson, B., & Decaro, M. S. (2012). The effects of feedback during exploratory mathematics problem solving: Prior knowledge matters. *Journal of Educational Psychology*, *104*, 1094–1108.
110. Fyfe, E. R., & Rittle-Johnson, B. (2016). Feedback both helps and hinders learning: The causal role of prior knowledge. *Journal of Educational Psychology*, *108*, 82–97.
111. Jansen, B. R. J., Louwerse, J., Straatemeier, M., Van Der Ven, S. H. G., Klinkenberg, S., & Van Der Maas, H. L. J. (2013). The influence of experiencing success in math on math anxiety, perceived math competence, and math performance. *Learning and Individual Differences*, *24*, 190–197.
112. Stoet, G., Bailey, D. H., Moore, A. M., & Geary, D. C. (2016). Countries with higher levels of gender equality show larger national sex differences in mathematics anxiety and relatively lower parental mathematics valuation for girls. *PLoS ONE*, *11*, e0153857.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mammarella, I. C., Caviola, S., Rossi, S., Patron, E., & Palomba, D. (2023). Multidimensional components of (state) mathematics anxiety: Behavioral, cognitive, emotional, and psychophysiological consequences. *Ann NY Acad Sci.*, 1–13. https://doi.org/10.1111/nyas.14982