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Numbers (but not words) make math anxious individuals sweat: Physiological evidence

Hili Eidlin Levy, Orly Rubinsten *

Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, Israel

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ABSTRACT

The study aimed to determine the specificity of math anxiety by measuring physiological arousal to the presentation of numerical and non-numerical stimuli. It also investigated whether math and trait anxieties share similar behavioral and physiological manifestations. Fifty-two female university students performed an experimental task including simple or complex arithmetical equations and math-related or neutral words. Participants' electrodermal activity (skin conductance response) was monitored during the task. Math and trait anxieties were measured using common explicit questionnaires. Results showed math anxiety levels were significantly related to physiological arousal during the performance of complex numerical tasks. Importantly, math anxiety significantly mediated the links between trait anxiety and physiological arousal in complex numerical tasks. The findings support previous work finding relations between math and trait anxieties, but also show math anxiety is a unique phenomenon with specific behavioral and physiological manifestations, especially during the processing of complex numerical information.

1. Introduction

Math anxiety "involves feelings of tension and anxiety that interfere with the manipulation of numbers…in a wide variety of ordinary and academic situations" (Richardson & Suinn, 1972). Math anxiety seems to be a situational fear of specific numeric stimulations, accompanied by cognitive changes (Ashcraft & Kirk, 2001; Ramirez, Gunderson, Levine, & Beilock, 2013) and possible physiological changes (Kucian, Mccaskey, Tuura, & Aster, 2018; Pizzie & Kraemer, 2017; Qu et al., 2020). Math anxiety affects individuals in a wide age range (Gunderson et al., 2018; Harari, Vukovic, & Bailey, 2013; Hart & Ganley, 2019; Zhang, Zhao, & Kong, 2019) and has been studied in the context of academic situations (Foley et al., 2017; Soltanlou et al., 2019) and well-being (Demirtaş & Uygun, 2020; Maloney & Beilock, 2012; Maloney & Retanal, 2020). There is broad agreement in the scientific community that math anxiety is not restricted to educational settings. A recent review (Rubinsten, Marciano, Eidlin-Levy, & Daches-Cohen, 2018) suggests math anxiety is a complex phenomenon, including emotional (e.g., Justicia-Galiano, Martín-Puga, Linares, & Pelegrina, 2017; Organization for Economic Co-operation & Development, 2013), educational (Lukowski et al., 2019; Zhang et al., 2019), attitudinal (e.g., Furner, 2019; Gunderson, Ramirez, Levine, & Beilock, 2011) and physiological aspects (e.g., Pizzie & Kraemer, 2017; Qu et al., 2020). Our study focused on these aspects.

Math anxiety has been shown to be specific to math-related situations (e.g., Ashcraft, 2002; Hill et al., 2016; Pizzie & Kraemer, 2019) and is evoked immediately (Pizzie & Kraemer, 2017; Rubinsten, Eidlin, Wohl, & Akibli, 2015) or even before the performance of math tasks (Klados, Pandria, Micheloyannis, Margulies, & Bamidis, 2015; Lyons & Beilock, 2012) and may have features similar to those of specific phobias (American Psychiatric Association, 2013).

Scientific evidence suggests individuals with high math anxiety levels may have distinct biological activation compared to individuals with low math anxiety levels (Kucian et al., 2018; Lyons & Beilock, 2012; Supekar, Iuculano, Chen, & Menon, 2015; Young, Wu, & Menon, 2012). However, physiological studies have inconclusive findings on anxiety-based physiological arousal in math anxiety. Early research by Dreger and Aiken (1957) found math anxiety relates to excessive physiological arousal during arithmetic task performance (Dreger & Aiken, 1957), but other researchers have failed to replicate these findings (Dew, Galassi, & Galassi, 1984; Qu et al., 2020; Strohmaier, Schiepe-Tiska, & Reiss, 2020).

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* Corresponding author at: Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa, 199 Aba Khoushy Ave., Mount Carmel, Haifa, Israel.

E-mail address: ORLY.RUBINSTEN@GMAIL.COM (O. Rubinsten).

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1.1. Math anxiety: physiological links

Fear responses frequently involve both emotional and psychophysiological changes (Stemmler, Heldmann, Pauls, & Scherer, 2001; Stone, 2010). Physiological fear symptoms include excessive blushing, excessive sweating, trembling, palpitations, and nausea (Muris, Hoeve, Meesters, & Mayer, 2004; Stone, 2010), the result of an increased autonomic arousal and increased heart rate (Hofmann & Kim, 2006; Hunkin, King, & Zajac, 2019; Lader, 1967; Rodríguez-Arce, Lara-Flores, Portillo-Rodríguez, & Martínez-Méndez, 2020; Roth, 2005).

The very few studies on math anxiety and psychophysiological activity refer mainly to changes in skin conductance levels. Only a handful of studies (Dew et al., 1984; Dreger & Aiken, 1957; Qu et al., 2020; Strohmaier et al., 2020) have simultaneously examined behavioral (numerical skills) and physiological responses in a highly emotional situation (e.g., numerical tasks). If we want to appreciate linkages across systems (behavioral and physiological), it is essential to employ a multi-method approach, combining both behavioral and physiological data. To this point, the conclusions of such research are inconsistent. Some early research in the field of math anxiety found excessive skin conductance on arithmetic task performance (Dreger & Aiken, 1957), while other work found weak relations between skin conductance and math anxiety only under test-like conditions (Dew et al., 1984).

Qu and colleagues (2020) recently investigated math anxiety and found elevated physiological arousal (measured by skin conductance) during the exam-anticipation period but not during the exam itself. In another recent study, Strohmaier and colleagues (Strohmaier et al., 2020) suggested motivational factors, such as the value attributed to the exam or the participant's sense of control, mediated the relations between math anxiety and elevated physiological arousal during exam anticipation. Similarly, research on cortisol secretion, another common biomarker of stress (Hellhammer, Wüst, & Kudielka, 2009), and math anxiety found indirect relations (Pletzer, Wood, Moeller, Nuerk, & Kerschbaum, 2010). Math anxiety and math abilities predicted performance on statistics exams for participants who showed increased cortisol levels prior to the test but not for those with decreased cortisol levels. The authors suggested changes in cortisol levels empowered the influence of math anxiety and math abilities on test scoring.

Findings of relations between math anxiety and physiological arousal are inconclusive, possibly because of differences in measurement settings (most studies measure physiological activity before or during pedagogical exams). As test-anxiety is common among students (for a meta-analysis, see Roos et al., 2020), it is important to conduct a physiological investigation in a numerical vs. non-numerical environment, not in a pedagogical exam setting.

1.2. Effect of environment on arousal: General (words and numbers) or specific (only numbers)?

Math anxiety is likely a multidimensional construct. In the state-trait model of anxiety (Spielberger, 1966), trait anxiety refers to an individual's predisposition to express negative emotions toward threats. State anxiety represents concurrent anxiety responses in the presence of specific threatening environmental stimuli (Lau, Eley, & Stevenson, 2006). In math anxiety, state anxiety responses are evident during math exams or math problem-solving (Bieg, Goetz, Wolter, & Hall, 2015; Goetz, Bieg, Lüdtke, Pekrun, & Hall, 2013; Orbach, Herzog, & Fritz, 2019, 2020). Physiological arousal is an indicator of state anxiety (Spielberger, 1972; Strohmaier et al., 2020) and thus should be evident among math anxious individuals when numerical stimuli are encountered. However, findings of elevated levels of fear in the presence of numerical information are inconclusive.

As math anxiety may have features similar to specific anxiety disorders, specific numeric stimulations, such as calculation (Ashcraft & Kirk, 2001; Lyons & Beilock, 2012) or math problems (Devine, Hill, Carey, & Szűcs, 2018; Mattarella-Micke & Beilock, 2010), should evoke fear reactions. Comprehensive research has also found words can be interpreted as having negative valence (Abado, Richter, & Okon-Singer, 2020; Palazova, Sommer, & Schacht, 2013; Zhang, Dong, & Zhou, 2018), and exposure to math-related words has been linked with fear reactions (Rubinsten, Bialik, & Solar, 2012; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2015). We aimed to replicate previous findings and to explore which stimuli, whether arithmetic or math-related words, evoke behavioral and physiological fear reactions. This would allow us to evaluate how specific math anxiety is.

To determine if math anxiety presents unique characteristics of fear reactions, we investigated first, if math anxiety is cognitively and physiologically linked to more generalized (trait) anxiety, and second, if math anxiety is specific to numerical information.

1.3. Math and trait anxiety: behavioral links

Is math anxiety linked to trait anxiety? Zettle and Raines (2000) suggested an association between math and trait anxiety, but others have found only moderate correlations (Betz, 1978; Núñez-peña & Bono, 2019) or no correlations at all (Wu, Barth, Amin, Malcarne, & Menon, 2012). Two cross-sectional studies found math anxiety and trait anxiety were positively correlated among primary school students and among older middle-school students (Carey, Devine, Hill, & Szűcs, 2017; Hill et al., 2016). However, math performance was specifically related to math anxiety over and above trait anxiety only for older students.

While the effect of trait anxiety on math performance is more prominent for younger students, accumulating negative experiences with math (e.g., via the influences of teachers, parents, peers, education systems) may strengthen and differentiate the relations between math anxiety and math performance (Dowker, Sarkar, & Looi, 2016). Research in this vein supports the assumption that trait anxiety is linked with math anxiety and even may act as a predisposition for it (Rubinsten, Eidlin-Levy, & Daches-Cohen, 2019).

Genetic studies may help determine whether trait anxiety is linked with math anxiety and possibly lead to the development of math anxiety. One study reported 9 % of the total variance in math anxiety resulted from genes related to general anxiety (Wang et al., 2014). However, in a recent genetic study, general (trait) anxiety did not account for the association between math anxiety and performance (Malanchini et al., 2020).

To this point, findings on the links between math anxiety and trait anxiety are inconclusive, and their behavioral and genetic links are not fully defined.

1.4. Numerical stimuli: math anxiety vs. trait anxiety

Importantly, trait anxiety can account for an individual's tendency to interpret numerical information as a threat. In behavioral studies, both trait anxiety (Owens, Stevenson, Norgate, & Hadwin, 2008) and math anxiety (Barroso et al., 2020; Carey, Hill, Devine, & Szucs, 2015; Foley et al., 2017; Hembree, 1990; Ma & Xu, 2004; Zhang et al., 2019) have been associated with low math achievements. Several studies have estimated the overlap between math anxiety and anxieties, such as trait or test anxieties, and their influence on math performance (Carey et al., 2017; Cargnelutti, Tomasetto, & Passolunghi, 2016; Devine, Fawcett, Szűcs, & Dowker, 2012; Hill et al., 2016; Núñez-peña & Bono, 2019). For example, Hill et al. (2016) found significant correlations between math anxiety and math, but not reading, performance among secondary school students after controlling for trait anxiety. Furthermore, math and not trait anxiety predicted performance in both basic (calculations) and more complex (math problems) math-related tasks (Miller & Bichsel, 2004). Following this line of research, we investigated if math or trait anxieties modulate behavioral and physiological activities in the presence of different numerical and non-numerical information.

1.5. The study

Our aim was to examine whether physiological and behavioral reactions to math anxiety are specific to numerical information while controlling for trait anxiety. To this end, we monitored participants' electrodermal activity (skin conductance levels or SCL). This is an indicator of physiological arousal commonly applied in basic research on emotion, such as anxiety states (for a review, see Benedek & Kaernbach, 2010a, 2010b), including academic anxiety, such as test anxiety (Roos et al., 2020).

To the best of our knowledge, this was the first study to measure event-related changes in skin conductance levels in math anxiety (previous research has mostly used a block-design method to record electrodermal activity). Event-related changes in skin conductance indicate stimulus-derived changes in arousal of the autonomic nervous system (Bach, Flandin, Friston, & Dolan, 2009). The event-related method enables separate measurement of possible changes in physiological arousal after the presentation of each stimulus. Accordingly, we were able to address the issue of whether different math-related stimuli (numerical and non-numerical) evoke similar physiological arousal. More specifically, we measured changes in skin conductance responses (SCRs) while participants processed arithmetic or non-arithmetic (words) stimuli (for a similar procedure, see Lyons & Beilock, 2012). We included math-related words and equations and neutral words.

We expected participants with high math anxiety levels would show higher physiological arousal than non-anxious ones (represented by higher amplitudes of skin conductance responses; Benedek & Kaernbach, 2010a) in arithmetic (equations) conditions, and this might accelerate with increased task complexity. We did not expect to find relations between math anxiety levels and physiological arousal for neutral words. For math-related words, we expected math anxiety would correlate with higher physiological arousal, thus suggesting all kinds of numerical stimuli, including numerical words (Rubinsten et al., 2015; Suárez-Pellicioni et al., 2015), evoke fear reactions, regardless of task type. That is, the mere presentation of numerical stimuli might evoke fear symptoms in math-anxious populations. In contrast, findings of similar physiological arousal for all participants (math-anxious and non-math-anxious) during the math-related word condition would indicate that only numerical tasks (e.g., calculations) evoke fear symptoms in math-anxious populations. On the behavioral level, we expected to replicate previous behavioral findings (Cates & Rhymer, 2003) whereby participants with high math anxiety levels would be less accurate and slower in the numeric but not the neutral condition. We also measured math fluency as an indicator of math proficiency (Rubinsten & Tannock, 2010; Woodcock, McGrew, & Mather, 2001), as this can influence behavioral responses.

Another aim was to investigate whether math anxiety is cognitively and physiologically linked to trait anxiety. We expected to find moderate correlations between reported math and trait anxiety levels (Betz, 1978; Hill et al., 2016; Núñez-peña & Bono, 2019). We further expected to replicate former findings and to find associations between trait anxiety and math anxiety in both behavioral (Foley et al., 2017; Owens et al., 2008; Zhang et al., 2019) and physiological (Qu et al., 2020; Roth, 2005; Strohmaier et al., 2020) measures.

Based on these expectations, we queried the degree to which math anxiety mediates trait anxiety and numerical knowledge. Following the argument that math anxiety is independent of trait anxiety and accounts for a decrease in math performance (Hill et al., 2016; Núñez-peña & Bono, 2019), we expected math anxiety would mediate the relations between trait anxiety and behavioral and physiological reactions.

2. Method

2.1. Participants

Fifty-eight females (*M* age = 26.13, *SD* = 2.82) participated in the study. All participants were undergraduate students, recruited through advertisements distributed on a university campus. Students were in diverse fields of study but all were taking math courses. We divided the math courses into proficiency level: low, intermediate, and high. Twelve participants were in math courses with a low proficiency level, 25 were in courses with an intermediate proficiency level, and 15 were in courses with a high proficiency level. All students had passing grades in math. Furthermore, all students reported they did not have a learning disability. All participants were right-handed. Data collection was conducted at the beginning of the spring semester.

Similar to previous research (e.g., Sheppes, Catran, & Meiran, 2009), only females were selected, as skin conductance levels (SCLs) significantly vary by gender (Iffland, Sansen, Catani, & Neuner, 2014; Venables & Mitchell, 1996), and females tend to be more emotionally expressive than males (Kring & Gordon, 1998). In addition, reports of high math anxiety levels are more common among females (Hill et al., 2016; Xie, Xin, Chen, & Zhang, 2019). Six participants were excluded because of missing data or EDA recording problems, leaving a final sample of 52 participants.

A statistical power analysis was performed for sample size estimation, based on data from previous related research. A meta-analysis by Roos and colleagues (Roos et al., 2020) found a medium effect size (r = .196, 95 % CI = .100–.289) between electrodermal activity and test anxiety. With alpha = .05 and power = 0.80, the calculated sample size needed for this effect size using G*Power software was approximately N = 42 for hierarchical regression analysis with two predictors, as in our research.

Participants were paid about 10USD for their participation. All participants gave written informed consent following the Declaration of Helsinki. The ethics committee approved the protocol of the University of Haifa (No. 048/16).

2.2. Measurements

2.2.1. Math anxiety: revised mathematics anxiety rating scale (MARS-R)

Participants answered a translated computerized version of the MARS-R (Plake & Parker, 1982), a shortened version of the MARS questionnaire (Richardson & Suinn, 1972) containing 30 items. We created a computerized version using an online Google Forms document; it was completed by participants after they performed the experimental task. The computerized version allowed us, among other things, to make sure participants did not miss any questions. The questionnaire was designed to reflect the degree of anxiety experienced in various math-related tasks and situations based on a 5-point scale (from 1, not nervous at all, to 5, very nervous). To obtain the total score, we simply summed up the scores for all questions (score range: 30–150; internal consistency reliability: α = .94). To avoid biased responses, we administered the MARS-R after the completion of the experimental task. Descriptive data appear in Table 1.

2.2.2. Trait anxiety: state-trait anxiety inventory (STAI)

Participants answered a translated computerized version of the State-Trait Anxiety Inventory (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). We selected 20 items measuring trait anxiety from the full STAI, which contains 40 items (the remaining 20 items measure state anxiety). We created the computerized version using an online Google Forms document. The questionnaire was designed to measure how an individual generally feels and to detect proneness to anxiety based on a 4-point scale (from 1, not at all, to 4, very much). To obtain the total score, we reversed the scale of 10 questions with positive phrasing (e.g., "I usually feel content") and summed up the scores for all questions (score range: 20–80; internal consistency reliability: α = .91). For descriptive data see Table 1.

2.2.3. Math fluency

We used the math fluency subtest of the Woodcock-Johnson III test of

Table 1
Descriptive Statistics of Behavioral and Physiological Data (N = 52).

		Min	Max	Mean	SD	Skewness
Math anxiety		30	124	70.73	19.94	.231
Trait anxiety		27	63	39.36	9.69	.523
Math fluency		65	120	97.57	11.46	−.392
Accuracy	Single digits	.69	1.00	.91	.08	−.998
	Double digits	.44	1.00	.75	.14	−.412
Rates (percentage)	Math words	.56	1.00	.87	.10	−.972
	Neutral words	.38	1.00	.90	.12	−2.431
Reaction times (in milliseconds)	Single digits	492.13	1753.14	1070.89	279.36	.282
	Double digits	610.64	2225.09	1354.19	359.83	.089
	Math words	680.38	2258.00	1232.92	349.69	.813
	Neutral words	630.12	1868.50	1229.06	321.40	.196
Physiological arousal (square roots of SCR amplitudes in Mus)	Single digits	1.34	36.71	12.56	9.73	.933
	Double digits	1.04	41.54	11.98	9.20	1.080
	Math words	1.09	33.23	12.18	9.18	.872
	Neutral words	1.00	39.71	13.10	9.43	.897

Note: Min = Minimum, Max = Maximum.

achievement (Woodcock et al., 2001), a standardized pen and pencil test, commonly used for math achievement testing (e.g., Rubinsten & Tannock, 2010). The subtest requires a rapid calculation of single-digit addition, subtraction, and multiplication and has a time limit of three minutes. Each item is scored as “1” or “0” based on accuracy; the summation of all correct items serves as the raw subtest score. Raw scores are converted into standard scores using a computerized program, with average of 100 and SD of 15 points.

2.3. *Data security*

Responses to the Google forms were stored in worksheets only accessible through the authors’ Google account login.

2.4. *Experimental task and stimuli*

Following previous research, we included *math-related* and *neutral* stimuli to investigate whether behavioral and physiological reactions were related to math anxiety levels. Specifically, we used both math-related words (as in Rubinsten et al., 2012, 2015) and math equations (as in Ashcraft & Kirk, 2001) as the math-related stimuli; we used neutral words as the non-math stimuli (the full list of stimuli appears in Appendix 1).

2.4.1. *Production of numerical stimuli*

There were four equation levels. The stimulus could be a single-digit arithmetic equation (e.g., 8-4), a double-digit (e.g., 52 + 16), a triple-digit (e.g., 536/268), or a power equation (e.g., 92 × 35). Each equation (single-, double-, triple-digit, or power) included at least one of four pairs of numbers (e.g., 8 and 4). Each pair of numbers produced four trials: each involved one of the four basic operations: addition, subtraction, multiplication, or division (e.g., the pair 8 and 4 produced the equations 8 + 4, 8-4, 8 × 4, and 48/4). Digit frequency (1–9) was controlled across all numerical combinations (for a detailed list of the numbers, see Appendix 1).

2.4.2. *Production of non-numerical (word) stimuli*

The word stimuli consisted of 16 math-related words and 16 neutral words. All words were chosen based on their frequency and emotional load as ascertained in preliminary research.

2.4.2.1. Pre-testing. Familiarity levels and emotional load of 30 math-related and 30 neutral words were tested by a short questionnaire distributed online (a Google Forms document) to a separate group of 58 university students. For each item, participants were asked how familiar a word was on a 9-point Likert scale (from 1, not familiar, to 9, very familiar) and how frightening a word was on a 9-point Likert scale (from 1, not frightening at all, to 9, very frightening). We used the 16 most frequently mentioned math-related words (Mean = 8.96, SD = .08). Then, we chose 16 neutral words, matching their length, i.e., number of letters, to the length of the math-related words (for detailed information, see Appendix 1). All neutral words were scored as very frequent (Mean = 8.99, SD = .005) and as carrying low emotional load (M = 1.04, M = .05).

2.4.3. *Construction of experimental task*

One of six stimulus types appeared on either the left or right side of the computer screen. These included five math-related stimulus types and a neutral stimulus type.

An identification task followed the equation or word presentation to make sure participants attended to the task. In this task, either one (i.e., *) or two asterisks (i.e., **) appeared on the screen (for an illustration, see Fig. 1), and participants were asked to decide if there were one or two asterisks by pressing the keyboard (Task 1 in Fig. 1). After participants responded to the identification task, the asterisks disappeared and either a number (after arithmetic stimuli) or a word (after non-arithmetic stimuli) appeared in the center of the computer screen. In number trials, participants were asked to determine whether the number was the correct answer to the previously presented equation (i.e., stimulus) or not (Task 2 in Fig. 1). In word trials, participants had to determine whether the word in the center of the screen rhymed with the previous word or not. This second task was presented to make sure that participants had processed the stimulus.

The main experimental task contained 16 experimental and two training blocks, each comprising one sample of each stimulus type (four equation levels, each with a different operation, math-related and neutral words). Operations (addition, subtraction, multiplication, and division) and stimulus location (right or left side) were counterbalanced

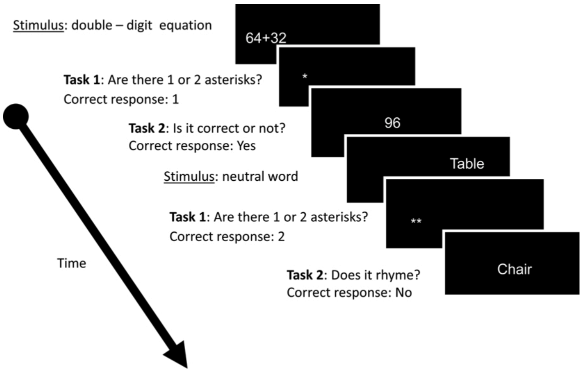

Fig. 1. Illustration of Experimental Task.

between blocks. The computerized program randomly chose experimental block order and gave a 20 s break, during which an aquarium film appeared on the computer screen, after four blocks were presented (24 trials). The break was terminated when participants pressed the space bar. Overall, the experimental task consisted of 96 experimental trials (4 equation levels (single-digit, double-digit, triple-digit, power) + 2 word levels (math, neutral) X 16) and lasted about 30 min. Twelve training trials were presented before the experimental trials.

2.5. Procedure

Each trial began with a white-colored square-shaped fixation point, presented for 750 ms (ms), followed by a blank screen presented for 100 ms. Then, a stimulus appeared on either the left or the right side of the screen and remained for 1000 ms. Next, there was an interstimulus interval (ISI) of 100−150 ms. The exact ISI changed between stimuli to avoid participants' prediction of the stimulus's appearance (Posner & Boies, 1971). A small stimulus (one or two asterisks) appeared either on the side previously occupied by the stimulus or on the opposite side of the screen. Participants were instructed to determine whether one or two asterisks appeared on the computer screen by pressing one of two optional keys on the keyboard (the numbers 1, 2). The asterisks remained on the computer screen until the participant responded or for 3000 ms. A number or a word then appeared in the center of the screen (Task 2; see Fig. 1), and participants had to determine whether the number/word was the correct answer to the equation/rhymed with the previous word or not and to press a matching key on the keyboard (1 for a correct answer; 2 for a wrong answer). After responding or after 4000 ms, a black screen appeared and remained for 1500 ms (for an illustration of the trials, see Fig. 1). Following this period, the next trial began.

2.6. Apparatus and physiological measurement

Skin conductance responses (SCRs), common representors of electrodermal activity, were measured as indicators of physiological arousal (Benedek & Kaernbach, 2010a, 2010b; Braithwaite et al., 2013). By applying constant voltage, the change in skin conductance can be measured non-invasively (Fowles et al., 1981). Studies show high anxiety levels are related to increased electrodermal activity (Dawson, Schell, & Filion, 2007; Felmingham, Rennie, Manor, & Bryant, 2011; Hofmann & Kim, 2006; Roth, Ehlers, Taylor, Margraf, & Agras, 1990). A recent meta-analysis investigating the autonomic features of emotions found SCRs as an indicator of autonomous reactions to fear have become more frequent in recent years (Siegel et al., 2018). These authors compared different measurements of fear and found a significant moderate increase in effect sizes of SCRs ($d = .61$, $P < .01$) compared to other autonomous measures (such as heart rate variability or diastolic blood pressure). A finding relevant to our research was that the measurement of mean skin conductance levels (SCLs) did not constitute a significant effect ($d = .19$, n.s.).

We used Biosemi active two-device electrodes (http://www.biosemi.com), connected to the distal phalanges of the index and middle fingers of the participant's non-dominant left hand. Common Mode Sense (CMS) and Driven Right Leg (DRL) electrodes were connected to the thenar and hypothenar areas of the left hand to enable data recording. All electrodes were attached using electrolyte gel (Electro-gel). Participants were requested to wash their hands before electrode attachment to ensure consistent hydration and to remove any dead skin that could increase electrical impedance (Dawson et al., 2007). After being seated in front of an IBM-PC terminal, the participants were connected to the electrodes. They were asked to wait quietly for five minutes to make sure the electrodes were connected properly and to allow them to become used to the experimental conditions (Boucsein, 1992).

2.7. Data analysis: dependent measures

2.7.1. Behavioral measures

2.7.1.1. Accuracy. We calculated mean scores for each stimulus type. Mean accuracy rates were higher than 80 % for math-related ($M = .88$, $SD = .17$) and neutral words ($M = .89$, $SD = .18$), as well as for single- ($M = .90$, $SD = .21$) and double-digit ($M = .81$, $SD = .22$) equations. However, mean accuracy rates were low for triple-digit ($M = .66$, $SD = .16$) and power equations ($M = .47$, $SD = .12$). Since we aimed to have all participants mentally process the stimuli and make sure they contained meaningful math data, we did not analyze triple-digit and power equations. We assumed that at some point, participants would ignore triple-digit and power equations, as they were too difficult or complicated to solve mentally. We also calculated mean error rates for each stimulus type.

2.7.1.2. Reaction times. Error trials were excluded from further analyses, as were trials that exceeded 3 SDs from mean scores. Then, we calculated the mean scores for each stimulus type. Note that the side of the presentation of the asterisks did not explain differences in reaction times to the experimental task ($F_{(2,51)} = 1.08$, $p = .303$, $\eta^2 = .021$) and did not interact with stimulus type ($F_{(2,51)} = 1.51$, $p = .224$, $\eta^2 = .086$). Hence, there was no congruency effect of Task 1 (see Fig. 1) on reaction times in Task 2.

2.7.2. Physiological measures

2.7.2.1. SCR analyses. SCR data were filtered with a unidirectional first-order Butterworth low pass filter with a cut-off frequency of 0.05 Hz and down-sampled to 8 Hz using the Brain Vision Analyser software (Brain-Products). For data processing and analysis, we used MATLAB 7.9.0 (MathWorks, Inc., Natick, MA) and the MATLAB-based toolbox Ledalab V3.4.2 (Leipzig, Germany), available online (www.ledalab.de). We used Continuous Decomposition Analysis (CDA) to enable the decomposition of skin conductance data into continuous signals of phasic and tonic activity. A minimum amplitude threshold criterion of 0.01 muS was applied (Braithwaite et al., 2013). We recorded significant SCRs within a response-window of 1–4 seconds after stimulus presentation, and we collected baseline SCRs from 0 to 1 s after stimulus presentation.

Following previous research, SCR amplitudes were chosen as an indicator of electrodermal activity (Benedek & Kaernbach, 2010b; Venables & Mitchell, 1996). For each trial, the baseline amplitude (from 0 to 1 s after the stimulus presentation) was subtracted separately from the amplitudes of the experimental epoch (1–4 s after stimulus presentation). Trials with no significant SCRs (i.e., amplitudes below 0.01 muS) were excluded from further analysis, as were trials that exceeded 3 SDs from mean scores. At this point, we calculated mean amplitude scores for each stimulus type (two arithmetic and two word types). Square root transformation was applied to normalize data and avoid skewed data (Braithwaite et al., 2013).

As no differences between operation type (addition, subtraction, multiplication, or division) were evident ($F_{(3,\ 171)} = .89$, $p > .449$, $\eta2 = .015$), even when trait ($F_{(3,\ 170)} = .19$, $p > .902$, $\eta2 = .002$) or math anxieties ($F_{(3,\ 170)} = .19$, $p > .907$, $\eta2 = .002$) were controlled, we excluded the operation type from further analysis.

2.8. Pre-analysis: associations between behavioral and physiological arousal

Previous research suggests skin conductance responses may represent behavioral responses rather than reactions to the emotional load of stimuli (Bach et al., 2009) and are sensitive to changes in the task's cognitive load (Frith & Allen, 1983) or the size of the stimulus (Codispoti

& Cesarei, 2007). Therefore, we correlated behavioral and physiological measures to account for the effect of non-emotional aspects of the stimulus on participants' performance (for detailed information, see Table 2).

For ACC rates, most of the correlations with physiological arousal were small and nonsignificant. The single exception was the negative correlation of math-related words and physiological arousal for the same type of stimulus (r(52)=−.338, p = .014, BF10 = 3.248). No correlation between RTs and physiological arousal was evident. Accordingly, elevated physiological arousal may not be related to changes in cognitive load of the stimulus, i.e., changes in stimulus size or behavioral reactions (Bach et al., 2009; Codispoti & Cesarei, 2007; Frith & Allen, 1983).

2.9. Data analysis: statistical plan to answer research questions

Based on our research hypotheses, trait and math anxieties were independent variables. Dependent behavioral measures included accuracy rates (ACC) and reaction times (RTs) of the experimental task. SCR amplitudes were physiological dependent measures. Each stimulus type was separately analyzed to measure whether stimulus modality (words or numbers) or complexity (single-digit or double-digit equations) affected physiological or behavioral responses.

2.9.1. Main analysis: research questions 1–2

The main objective was to investigate the association between math anxiety levels and physiological arousal while controlling for trait anxiety. Thus, we conducted correlation tests for behavioral (research question 1A) and physiological measures (research questions 1B), followed by hierarchical regression analyses (research question 2) with the Enter method on the entire sample (N = 52) to explore how math anxiety and trait anxiety contributed to the variance in physiological arousal. For each analysis, we entered trait anxiety into the equation in the first step and added math anxiety in the second step. We performed mediation analyses to determine whether math anxiety mediated the association between trait anxiety and physiological arousal.

2.9.2. Group difference analysis: research question 3

To strengthen the results for questions 1 and 2, we conducted group analysis. Note that we used three groups for the third research question only. We employed MAVOVA tests to detect differences between participants with high (N = 18), intermediate (N = 16), and low (N = 18) math anxiety levels. Math anxiety was the independent variable, and stimulus types (single- or double-digit equations, math and neutral words) were dependent variables. As the covariance between dependent variables is accounted for in MANOVA tests (Stevens, 2002), we could tell whether math anxiety levels simultaneously explained differences in various behavioral and physiological measures. We used Roy's largest root test for significance, as it has the best fit for correlated dependent variables (Huberty & Olejnik, 2006). A series of follow up univariate ANOVA tests indicated whether the independent viable explained differences in each specific dependent variable.

Table 2
Correlations between Behavioral and Physiological Measurements (N = 52).

Stimuli	Measurements	RTs (p, BF10)	SCR (p, BF10)
Single digits	ACC	−.268 (.055, 1.034)	−.084 (.552, .206)
	RTs		.131 (.355, .262)
Double digits	ACC	−.203 (.149, .467)	.051 (.719, .184)
	RTs		.147 (.299, .292)
Math-related words	ACC	**−.534 (<.001, .556)**	**−.338 (.014, 3.238)**
	RTs		.198 (1.59, .455)
Neutral words	ACC	**−.401 (.003, 11.76)**	−.036 (.799, .178)
	RTs		.009 (.947, .173)

Note: ACC = accuracy rate, RT = reaction time.

2.9.2.1. Group creation.

2.9.2.1. Group creation. Since the literature does not set a clear threshold for high math anxiety levels and based on previous studies (e.g., Cates & Rhymer, 2003; Rubinsten et al., 2015;), we used a percentile-based (tertile split) method to classify participants as having high, intermediate, or low math anxiety levels. Participants in the bottom third of the sample were classified as having low math anxiety levels (N = 18, scores range = 30–61, *M* = 49.94). Participants from the intermediate third of the sample were classified as the intermediate group (N = 16, score range = 62–78, M = 70.31). Participants in the top third of the sample were classified as having high math anxiety levels (N = 18, scores range = 79–124, *M* = 91.88) (for a similar classification method, see Ashcraft & Krause, 2007; Zakaria & Nordin, 2008).

2.9.3. Interpretation of results

To address recent requests to combine several statistical methods to calculate the probability with which findings favor the research hypothesis over the null hypothesis (Vandekerckhove, Rouder, & Kruschke, 2018; Wasserstein & Lazar, 2016), we calculated Bayes factors for the analyses. Bayes factors express the ratio between the evidence in favor of the hypothesis and the null hypothesis. For Bayes factor interpretation, we adopted the classification recommended by Wagenmakers et al. (2018). We interpreted results using the following strategy: results which reached a significant p value and a Bayes index above 3 were considered robust and supported the theory; results which reached a marginal p value (.05 < p < .1) (Olsson-Collentine, van Assen, & Hartgerink, 2019) or an inconclusive Bayes factor (between 1 and 3) were inconsistent and required further analysis; results with a nonsignificant p value or a Bayes index smaller than 1 supported the null hypothesis.

3. Results

3.1. Research question 1A

The first research question sought to specify the relations between math anxiety, trait anxiety, and behavioral math performance. One of the main objectives was to investigate the links between math anxiety and math performance, while controlling for trait anxiety. To address this question, we performed correlational analysis on the entire sample (N = 52), followed by hierarchical regression and mediation analysis.

3.1.1. Relations between math and trait anxieties

Correlations of the behavioral variables appear in Table 3. The correlation between math anxiety and trait anxiety was significant, although Bayesian analysis did not support the theory and thus suggested inconclusive findings (*r(52)* = .353, *p* = .009, BF10=2.161).

3.1.2. Relations between math anxiety and numerical and non-numerical stimuli

The relations between math anxiety and math fluency were marginally significant but did not reach Bayes factor significance levels (*r*(52) = .−.253, *p* = .067, BF10=.710). Therefore, we concluded the link between math anxiety and math fluency was not significant.

In the experimental task, math anxiety levels were not correlated with accuracy rates for either stimulus type (see Table 3). However, those with higher math anxiety levels were faster in responding to all experimental stimuli (i.e., single- and double-digit equations, as well as math-related and neutral words; see Table 3). It is important to note, though, that the pattern of the Bayesian factors indicated the link between math anxiety levels and RTs in each one of the four stimulus types was strongest for the more difficult numerical stimuli, i.e., the double-digit equations (***r**(52)* = .348, *p* = .011, BF10=2.887), and inconclusive for the other conditions (single-digit: *r(52)* = .275, *p* = .046,

Table 3
Correlation Matrix for Anxiety Measures and Behavioral Measures of Experimental Task (N = 52).

		1	2	3	4	5	6	7	8	9	10	11
1	Math anxiety		.353**	−.253	−.107	−.072	−.183	−.213	.275*	.348*	.284*	.319*
2	Trait anxiety			−.040	.085	.112	−.038	−.053	.165	.245	.115	.126
3	Math fluency				.300*	.318	.196	.304*	−.564**	−.492**	−.406**	−.432**
4	ACC – single digits					.421**	.255	.278*	−.280*	−.151	−.207	−.178
5	ACC – double digits						.025	.198	−.381*	−.214	−.184	−.192
6	ACC – math words							.457**	−.300*	−.405**	−.540**	−.569**
7	ACC – neutral words								−.333*	−.316**	−.587**	−.411**
8	RT – single digits									.758***	.753***	.790***
9	RT – double digits										.772***	.851***
10	RT – math words											.926***
11	RT – neutral words											

Note: ACC = accuracy rate; RT = reaction time; significance: * = p < .05, ** = P < .01, *** = P<.001.

BF10=.885; math words: $r(52) = .284$, $p = .039$, BF10=1.090; neutral words: $r(52) = .319$, $p = .020$, BF10=1.555).

We performed partial correlations to control for the influence of math fluency and found it correlated with RTs for all experimental stimuli (see Table 4). When math fluency was controlled, math anxiety was significantly correlated with double-digit equations (r $r(52) = .254$, $p = .036$, BF10=1.68), but not with other stimulus types (single digits: $r(52) = .152$, $p = .152$, BF10=.516; math words: $r(52) = .198$, $p = .082$, BF10=.820; neutral words: $r = .221$, $p = .060$, BF10=1.066).

3.1.3. Relations between trait anxiety and behavioral measures

Trait anxiety did not significantly correlate with any of the behavioral measures (see Table 4). Thus, no further regression analyses were conducted for behavioral data.

3.1.4. Research question 1A conclusion

Higher math anxiety levels were associated with slower responses to the more complex double-digit equations, even when math fluency was controlled. Importantly, we did not find an association between trait anxiety levels and behavioral measures in this sample.

3.2. Research question 1B

The second part of the first research question asked about the associations between math anxiety, trait anxiety, and physiological arousal. Table 4 summarizes the correlations between anxiety measures and physiological measures. Math and trait anxieties were significantly correlated with all physiological measures across different experimental stimuli. Accordingly, higher anxiety levels were linked with higher physiological arousals (as represented by SCR amplitudes) for all the experimental variables (Table 4).

3.2.1. Relations between math anxiety and physiological arousal

Only a few significant correlations were supported by Bayes factor analysis (see Table 4). Specifically, math anxiety levels were significantly and positively correlated with the more difficult double-digit equations ($r(52) = .372$, $p = .007$, BF10=.6.286), indicating moderate to strong support of the theory, and with math words ($r(52) = .341$, $p = .016$, BF10=3.397), suggesting moderate support. In contrast, while the relations between math anxiety and the easier single-digit equations ($r(52) = .291$, $p = .019$, BF10=2.161) and neutral words ($r(52) = .325$, $p = .046$, BF10=2.524) were significant, Bayesian analysis suggested inconclusive findings.

3.2.2. Relations between trait anxiety and physiological arousal

Trait anxiety was significantly correlated with single-digit equations ($r(52) = .359$, $p = .009$, BF10=4.814), giving moderate support of the theory. The associations with double-digit equations ($r(52) = .301$, $p = .030$, BF10=1.669), math-related words ($r(52) = .317$, $p = .022$, BF10=2.220), and neutral words ($r(52) = .309$, $p = .026$, BF10=1.927) were significant, but Bayesian analysis suggested inconclusive findings.

3.3. Research question 2

The second research question asked if math anxiety and trait anxiety differently contribute to variance in physiological arousal. We conducted a series of hierarchical regression analyses to measure the contribution of trait anxiety and math anxiety to physiological arousal variance. Summaries of the regression analyses appear in Tables 5 (numerical stimuli) and 6 (word stimuli).

3.3.1. Single-digit equations

For the single-digit equations (left side of Table 5), trait anxiety predicted 12.9 % of variance in physiological arousal ($\beta = .359$, $t = 2.722$, P = .009, BF10 = 5.262). Surprisingly, math anxiety did not make a unique contribution to the variance for this stimulus type: when trait anxiety and math anxiety were simultaneously entered as predictors of physiological arousal, trait anxiety remained a significant predictor of physiological arousal ($\beta = .297$, $t = 2.16$, P = .036, BF10 = 3.468), whereas math anxiety was not significant in the equation ($\beta = .197$, $t = 1.43$, $P = .158$, BF10=1.346).

3.3.2. Double-digit equations

For double-digit equations (right side of Table 5 and Fig. 2A), the more complex numerical stimuli, trait anxiety predicted 9.1 % of variance in physiological arousal ($\beta = .301$, $t = 2.23$, P = .030, BF = 2.062).

Table 4
Correlations Matrix for Anxiety Measures and Physiological Data (N = 52).

	Trait anxiety		Single digits		Double digits		Math words		Neutral words	
	R	BF10	R	BF10	R	BF10	R	BF10	R	BF10
Math anxiety	.353**	2.161	.291*	1.458	.372**	6.286	.341*	3.397	.325*	2.524
Trait anxiety			.359**	4.814	.301*	1.669	.317*	2.220	.309*	1.927
Single digits					.825**	1.42	.894***	1.105	.891***	5.714
Double digits							.829***	2.386	.802***	9.858
Math words									.861***	2.216
Neutral words										

Note: Significance levels: * P < .05; ** P < .01.

Table 5
Contribution of Trait and Math Anxieties to Physiological Arousal Variance of Arithmetic stimuli: Summary of Hierarchical Regression Analysis.

	Single Digits							Double Digits						
Predictors	β	*T*	P	BF10	R^2	ΔR^2	ΔF	β	*T*	P	BF10	R^2	ΔR^2	ΔF
Step 1					.129	.129	7.407**					0.91	.091	4.976*
Trait anxiety	.359	2.722	.009	5.262				.301	2.231	.030	2.062			
Step 2					.130	.035	2.057					.176	.085	5.081*
Trait anxiety	.297	2.157	.036	3.468				.204	1.490	.143	1.470			
Math anxiety	.197	1.434	.158	1.346				.308	2.254	.029	4.293			

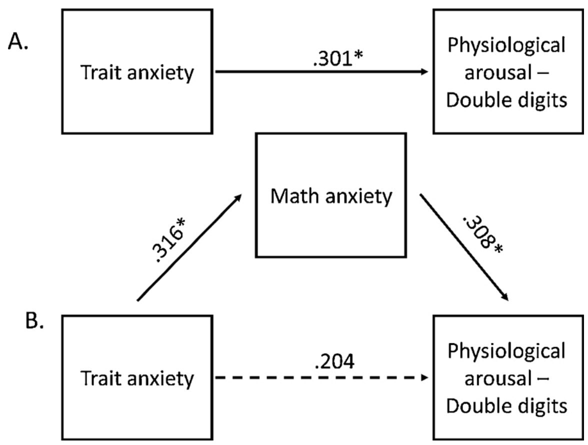

Fig. 2. *A*. Illustration of Direct Effect between Trait Anxiety and Physiological Arousal for Double-Digit Equations. Trait anxiety predicted 9.1 % of variance (β = .301, *t* = 2.23, P = .030, BF = 2.062). *B*. Illustration of Mediation Design. Trait anxiety did not remain a significant predictor of physiological arousal (β = .204, *t* = 1.49, P = .143, BF10 = 1.470), but math anxiety was significant (β = .308, *t* = 2.25, *P* = .029, BF10=4.293). Hence, trait anxiety showed an indirect effect on physiological arousal through math anxiety (95 % CI: .011–.255; P=.026, as tested by a bias-corrected bootstrap procedure).

Math anxiety predicted another 8.5 %, while the entire model predicted 17.6 %.

Importantly, when trait anxiety and math anxiety were simultaneously entered as predictors of physiological arousal, trait anxiety did not remain a significant predictor (β = .204, *t* = 1.49, P = .143, BF10 = 1.470), but math anxiety remained significant in the equation (β = .308, *t* = 2.25, *P* = .029, BF10=4.293), giving moderate support of the theory. Note that in the mediation analysis (see Fig. 2B), the reduction in the direct relations between trait anxiety and physiological arousal was significant (95 % CI: .011–.255; P = .026, as tested by a bias-corrected bootstrap procedure).

3.3.3. *Math-related words*

For math-related words (left side of Table 6), trait anxiety explained 10.1 % of variance in physiological arousal (β = .317, *t* = 2.36, P = .022, BF10 = 2.619). When trait anxiety and math anxiety were simultaneously entered as predictors, trait anxiety did not remain a significant predictor of physiological arousal (β = .233, *t* = 1.69, P = .097, BF10 = 1.847), nor did math anxiety (β = .268, *t* = 1.95, *P* = .057, BF10=2.600), as its contribution was marginally significant.

3.3.4. *Neutral words*

For neutral words (right side of Table 6), trait anxiety explained 9.5 % of variance in physiological arousal (β = .309, *t* = 2.29, P = .025, BF10 = 2.307). When both trait and math anxieties were entered into the equation, the change in variance was not significant. Specifically, trait anxiety did not remain a significant predictor of physiological arousal (β = .229, *t* = 1.65, P = .105, BF10 = 1.653), nor did math anxiety (β = .252, *t* = 1.82, *P* = .075, BF10=.075).

3.4. *Research question 3*

The third question concerned possible differences between different math anxiety levels in the context of numerical and non-numerical stimuli.

3.4.1. *Effect of math anxiety levels on the behavioral level*

According to univariate ANOVA tests and as detailed in Table 7, participants with high, intermediate, and low math anxiety levels had similar trait anxiety levels and similar scores in the math fluency test. A MANOVA test showed math anxiety levels explained differences in accuracy rates in the experimental task (Roy's largest root = .314, $F_{(4,47)} = 3.69$, $p = .011$, $\eta^2 = .239$). However, none of the follow-up ANOVA tests were significant, and we did not conduct post hoc tests.

We found group differences in reaction times in the experimental task (Roy's largest root = .252, $F_{(4,47)} = 2.96$, $p = .029$, $\eta^2 = .201$). According to follow-up univariate ANOVA tests, group differences were evident for double-digit equations exclusively (see Table 7). According to Tukey post hoc tests, participants with high math anxiety levels were significantly slower than participants with low math anxiety levels ($p = .013$). No significant difference emerged between the intermediate group and the other groups. A similar trend was evident for single-digit equations, although results were marginally significant. No group differences were evident for words, either math or neutral.

To summarize, high math anxiety individuals were significantly slower than low math anxious individuals on numerical (more complex double-digit equations) but not on word stimulus tasks.

3.4.2. *Physiological arousal and high math anxiety levels*

Similar to the behavioral findings and as indicated in Table 7, the physiological measures showed math anxiety levels had a significant effect on physiological arousal (measured by SCR amplitudes) (Roy's largest root = .234, $F_{(4,47)} = 3.61$, $P = .042$, $\eta^2 = .190$). The follow-up

Table 6
Contribution of Trait and Math Anxieties to Physiological Arousal Variance of Word Stimuli: Summary of Hierarchical Regression Analysis.

	Math Words							Neutral Words						
Predictors	β	*T*	P	BF10	R^2	ΔR^2	ΔF	β	*T*	P	BF10	R^2	ΔR^2	ΔF
Step 1					.101	.101	5.590*					0.95	.095	5.264*
Trait anxiety	.317	2.364	.022	2.619				.309	2.294	.025	2.307			
Step 2					.131	.065	3.875					.153	.057	3.314
Trait anxiety	.233	1.691	.097	1.847				.229	1.653	.105	1.685			
Math anxiety	.268	1.946	.057	2.600				.252	1.821	.075	2.079			

Table 7
Group Differences between Participants with High, Intermediate, and Low Math Anxiety Levels.

Test		Math Anxiety Levels			F test	P-value	Size effect (η^2)	BF10
[MAVOVA test]		High N=18 *M (SD)*	Intermediate N=16 *M (SD)*	Low N=18 *M (SD)*				
Trait anxiety (STAI)		42.11 (11.30)	38.68 (9.08)	37.22 (8.25)	1.211	.307	.05	.357
Math fluency		94.50 (12.11)	96.87 (10.29)	101.27 (11.34)	1.658	.201	.06	.492
Experimental task: **accuracy rates** [$F_{(4,47)}$=3.693, p=.011, η^2=.239]	Single digits	.89 (.09)	.93 (.08)	.93 (.07)	1.418	.252	.05	.413
	Double digits	.71 (.14)	.79 (.14)	.76 (.15)	1.007	.373	.03	.306
	Math words	.88 (.11)	.82 (.11)	.90 (.07)	3.046	.057	.11	1.263
	Neutral words	.87 (.16)	.92 (.06)	.90 (.11)	.758	.474	.03	.256
Experimental task: **reaction times** [$F_{(4,47)}$=2.964, p=.029, η^2=.201]	Single digits	1185.11 (233.06)	1060.67 (295.45)	965.75 (277.81)	3.010	.058	.11	1.728
	Double digits	**1478.63 (373.11)**	**1444.10 (303.49)**	**1149.84 (315.83)**	**5.219**	**.009**	**.18**	**5.777**
	Math words	1329.54 (352.14)	1243.34 (327.32)	1127.05 (355.62)	1.552	.222	.06	.456
	Neutral words	1320.43 (316.39)	1276,79 (310.22)	1095.27(308.11)	2.620	.083	.09	.969
Experimental task: **SCR amplitudes** [$F_{(4,47)}$=2.696, p=.042, η^2=.190]	Single digits	15.74 (11.19)	11.05 (8.83)	10.72 (8.57)	1.257	.294	.05	.871
	Double digits	**16.30 (11.37)**	**10.63 (8.55)**	**8.85 (5.32)**	**3.527**	**.037**	**.13**	**2.994**
	Math words	15.52 (10.88)	11.67 (8.80)	9.29 (6.74)	2.269	.114	.09	1.463
	Neutral words	17.06 (10.30)	11.08 (7.92)	10.95 (8.95)	2.600	.085	.10	1.794

univariate ANOVAs revealed a significant difference for double-digit equations. According to a Tukey post hoc test, the high math anxiety group had significantly higher SCRs than the low math anxiety group, indicating increased arousal among participants with high math anxiety (p = .037). No differences appeared between the intermediate group and the other groups. Furthermore, there were no group differences for single-digit equations or for math or neutral words.

As in the behavioral analysis, the physiological analysis showed the significant difference between high and low math anxiety groups appeared mainly for the most difficult numerical stimuli, namely the double-digit equations. Arguably, prime numerical complexity (double but not single digits) and modality (numbers but not words) modulate physiological arousal in math anxiety. That is, high math anxiety individuals are physiologically more aroused when processing more challenging mathematical stimuli (for specific details, see Table 7).

4. Discussion

The primary purpose of the study was to determine whether females with math anxiety showed a unique physiological arousal in the presence of numerical stimuli in addition to having links with trait anxiety. The results clearly indicate that in the context of a visual mathematical equation, higher math anxiety levels were significantly linked with higher physiological arousal levels in our participants. This pattern of physiological arousal did not extend to the neutral word stimuli.

The results have important implications for the theoretical understanding of math anxiety in females, who commonly report higher math anxiety levels than males (Hill et al., 2016; Xie et al., 2019) and are more vulnerable to the effects of math anxiety (e.g., Levy, Fares, & Rubinsten, 2021). Two main ideas lie at the heart of the dominant account of math anxiety. First, math anxious individuals are understood to have general difficulty with mathematics (the math anxiety-math performance link) (Barroso et al., 2020; Foley et al., 2017; Zhang et al., 2019). Second, math anxiety has been linked with trait anxiety (Hill et al., 2016; Rubinsten et al., 2019; Zettle & Raines, 2000). Our data significantly challenge the first claim: participants with math anxiety showed increased physiological arousal but mainly in the presence of more complex numerical information (i.e., double-digit equations). Physiological arousal is a reliable indicator of increased activity of the autonomic nervous system, activated when the individual is facing an immediate threat (Rodríguez-Arce et al., 2020; Roth, 2005; Siegel et al., 2018; Stemmler et al., 2001; Strohmaier et al., 2020). Thus, our findings reveal that contrary to existing hypotheses, the effects of math anxiety may extend to physiological arousal in the processing of complex arithmetic information. It should be noted that Ashcraft and colleagues' findings (Ashcraft & Kirk, 2001; Ashcraft, Kirk, & Hopko, 1998; Ashcraft, Krause, & Hopko, 2007) behaviorally support our physiological data, as these researchers failed to find a behavioral difference for single-digit arithmetic, while math anxious individuals only had difficulty with complex mathematics (such as multi-digit arithmetic problems).

The second core idea is that math anxiety is related to trait anxiety both genetically (Wang et al., 2014) and cognitively (Carey et al., 2017; Hill et al., 2016; Szczygieł, 2020). Our findings expand the model and show math anxiety levels mediate the link between trait anxiety and physiological arousal in the face of complex numerical information. Our discovery that math anxiety mediates the link between trait anxiety and physiological arousal in a very specific and complex numerical environment suggests the need to reconceptualize the developmental trajectory of math anxiety. Specifically, math anxiety could result from exposure to adverse math learning experiences and low achievements in intrinsically biologically vulnerable individuals (i.e., those showing a tendency towards trait anxiety) who are at risk for developing math anxiety (Rubinsten et al., 2018, 2019). The hypothesis that math anxiety results from a tendency to interpret the numerical world as affectively negative, while not new (Carey et al., 2017; Rubinsten et al., 2019; Szczygieł, 2020), has mostly been abandoned in recent years. Future research should seek to develop a better understanding of this putative early deficit, for example, by investigating the effects of math and trait anxiety on fundamental mathematical or number tasks.

4.1. Inflated physiological arousal in math anxiety is specific to numeric information

The design of the research enabled us to monitor changes in physiological arousal caused by different stimulus types, arithmetic and otherwise. Different patterns emerged for different numerical stimuli. In the arithmetic tasks, high math anxiety levels were systematically accompanied by high physiological arousal for the more complex double-digit equations. We did not have similar results for single-digit equations. Solving a single-digit equation requires retrieving arithmetic facts, a cognitive process that is often automatic in numerically skilled individuals (Kaufmann & von Aster, 2012; King & Janiszewski, 2011). All participants were university students, and their scores in the fluency task (see Table 2 for detailed information) were within the normal range, except for five participants, who were assigned to either high or low math anxiety levels. Accordingly, we assume our participants had good numerical skills, enabling automatic retrieval of arithmetic facts. Furthermore, we found no differences between the type of operation (i.e., addition, subtraction, multiplication, or division) and no interaction between operation type and math or trait anxieties. There was also no group difference (high vs. low math anxiety levels) in accuracy rates for different stimulus types. This pattern of results supports the assumption that our participants had sufficient math proficiency. Even so, our results are relevant mostly to similar populations, such as higher education students, who have adequate math proficiency.

Double-digit equation computation requires procedural knowledge, and this demands more working memory resources (DeCaro, Rotar, Kendra, & Beilock, 2010). According to the scientific literature, high math anxiety levels interfere with the working memory processes involved in math computation (Ashcraft & Kirk, 2001; Pelegrina, Justicia-Galiano, Martín-Puga, & Linares, 2020; Ramirez et al., 2013). Our findings replicate former findings and indicate math anxiety's interference in complex, high-working memory load computations is accompanied by inflated physiological arousal.

We had mixed results for the non-numerical tasks. Participants with high math anxiety levels showed a tendency to experience greater arousal when exposed to math-related words but not to neutral words. However, Bayesian analysis only partially supported this, so the results are not robust. It is possible that not all math-related words carried a heavy negative load (for example, the word "roots" has other, non math-related meanings), and this may have reduced the group's mean scores and precluded robust results. Nevertheless, to some degree, the findings extend former research and show math-related words such as "algebra" or "percentage" can evoke negative emotion, exhibited on both behavioral (Rubinsten et al., 2015; Suárez-Pellicioni et al., 2015) and physiological levels. As no similar results appeared for neutral words, high physiological arousal may not be attributed to non-emotional changes in the cognitive load of the stimuli, with respect to either stimulus size or behavioral reactions (Bach et al., 2009; Codispoti & Cesarei, 2007; Frith & Allen, 1983).

Overall, the findings follow those of previous research and emphasize the relations between specific fear and increased physiological arousal (Hofmann & Kim, 2006; Lueken et al., 2011). Furthermore, this acceleration in physiological arousal was specific to math-related and not neutral stimuli among our participants (Dreger & Aiken, 1957). Further research is needed to strengthen our results, but they suggest individuals with high math anxiety levels exhibit accelerated physiological arousal when they face more complex math stimuli (Ashcraft & Kirk, 2001).

4.2. Math and trait anxieties' links with behavioral and physiological reactions

Echoing previous work (Betz, 1978; Hill et al., 2016; Núñez-peña & Bono, 2019), our study showed reported math anxiety levels positively and moderately correlated with trait anxiety levels (although Bayesian analysis was not conclusive). Regression analyses revealed these two constructs related differently to behavioral and physiological manifestations. Math anxiety mediated the relations between trait anxiety and physiological arousal in the double-digit condition. Math anxiety also marginally predicted physiological arousal in the math-related word condition, but trait anxiety was not a significant predictor. Surprisingly, trait and not math anxiety predicted physiological arousal in the single-digit condition. As mentioned earlier, single-digit equations require arithmetic fact retrieval. Trait anxiety can cause ineffective retrieval in certain situations (Garibbo, Aylward, & Robinson, 2019), and affect arithmetic fact retrieval, as evident in our research.

Based on our findings, we argue that math and trait anxiety interfere with numerical performance in different ways, and different physiological mechanisms identify specific and general anxieties (Brown, Chorpita, & Barlow, 1998). Trait anxiety interferes with arithmetic fact retrieval, similar to other retrieval problems associated with trait anxiety (Garibbo et al., 2019). Math anxiety interferes with complex computations, as it interferes with working memory processes (Ashcraft & Kirk, 2001; Pelegrina et al., 2020; Ramirez et al., 2013). While trait anxiety can also interfere with working memory processes (Moran, 2016), the effect of math anxiety is more specific and prominent during the performance of complex computations, as demonstrated by the mediation analysis. Hence, the results strengthen the assumption that high math anxiety levels hinder math performance over and above the influence of trait anxiety (Hill et al., 2016). Although trait anxiety probably acts as a predisposition for math anxiety development at a young age, math anxiety is a unique phenomenon with specific manifestations among older students (Carey et al., 2017; Rubinsten et al., 2019).

In our study, trait anxiety did not relate to any behavioral measure. In contrast, high math anxiety levels related to slower reactions times for more complex double-digit equations, a pattern which remained robust in both variance and correlation tests. The relations between math anxiety and response time to double-digit equations appeared even when we controlled for math fluency, an indicator of numerical proficiency, which correlated with response times over the experimental task. Hence, we can confidently argue that math anxiety levels hinder performance of complex double-digit equations above and beyond general math fluency.

There were no significant relations between math anxiety reaction times for other stimulus types or for accuracy levels. The evidence strengthens the assertion that math anxiety mostly hinders the performance of complex arithmetic tasks (Ashcraft & Kirk, 2001; Ashcraft et al., 1998, 2007). Some researchers have suggested the relations between math anxiety and numerical competence are not straightforward but influenced by other emotional aspects, such as motivation (Gunderson et al., 2018; Wang et al., 2015) and individuals' latent profiles (Carey et al., 2017). Our findings provide evidence that high math anxiety levels are not necessarily accompanied by poor numerical performance. The students participating in the research may have had some resilience factors, such as high motivation toward math performance, and this may have prevented a reduction in their math ability. Unfortunately, we did not assess other emotional factors, such as motivation or self-efficacy, so this question remains open.

The findings emphasize the need to use a multi-method research design, including both state and trait measures of math anxiety (2020, Bieg et al., 2015; Orbach et al., 2019; Strohmaier et al., 2020), to get a better understanding of math anxiety's behavioral and physiological manifestations.

4.3. Suggestions for future research

It should be noted that only females enrolled in higher education studies were included in the study; future research should attempt to replicate the results with males and determine whether there are gender differences in the physiological arousal exhibited by high math-anxious individuals. Such a study could also address whether gender differences are more prominent in explicit than implicit anxiety measures (Vianello, Schnabel, Sriram, & Nosek, 2013). Future research should examine a less educated population and include non - educational settings. Field research is required to test the ecological validity of the findings as well (Roos et al., 2020). In addition, the current research involved a single physiological arousal measure (SCR). Thus, it is essential to explore the impact of math anxiety on other physiological arousal measures as cardio-vascular or respiratory parameters (Hunkin et al., 2019; Iffland et al., 2014; Rodríguez-Arce et al., 2020) to get a more precise concept of the associations between math anxiety and physiological arousal.

The study specifically investigated the links between math anxiety and behavioral and physiological measures. While trait anxiety was controlled in this study as in other work (e.g., Hill et al., 2016), most studies investigating math anxiety (or other specific anxiety disorders; e.g., Landová et al., 2020; Trost et al., 2017; Watson et al., 2019) do not control for other anxiogenic processes. Future comparisons of math anxiety with other specific anxieties or phobias, such as social anxiety or animal phobia, would expand knowledge of the mechanisms and manifestations of math anxiety.

4.4. Conclusions

We have clearly demonstrated that reported math anxiety levels are related to increased physiological arousal (as in Dreger & Aiken, 1957; Qu et al., 2020) when females are performing math-related tasks. Our findings constitute another layer (physiological) in math anxiety research, suggesting math anxiety may be considered a situation-related phenomenon, with specific behavioral, cognitive, and physiological manifestations (Rubinsten et al., 2018) affecting individuals' performance.

Using the processing of numerical and non-numerical stimuli, we have demonstrated that individuals with high math anxiety levels differ from those with low math anxiety in their levels of physiological arousal during the presentation of complex arithmetic but not neutral words. Furthermore, these differences appear to mediate the links between trait anxiety (and possibly the tendency to interpret the world as emotionally negative) and physiological arousal during the presentation of complex numerical equations. The data suggest the effect of math anxiety extends beyond the level of mathematical performance and into physiological arousal, typically evident in general anxiety, and the links between trait anxiety and physiological arousal in complex arithmetical environments are mediated by math anxiety.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.biopsycho.2021.108187.

References

Abado, A., Richter, T., & Okon-Singer, H. (2020). Attention biases toward negative stimuli. In A. Aue, & H. Okon-Singer (Eds.), *Cognitive biases in health and psychiatric disorders: Neurophysiological foundations* (pp. 19–40). Elsevier.

American Psychiatric Association. (2013). *DSM 5*. American Psychiatric Association.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science, 11*(5), 181–185. https://doi.org/10.1111/1467-8721.00196

Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General, 130*(2), 224–237. https://doi.org/10.1037/0096-3445.130.2.224

Ashcraft, M. H., & Krause, J. A. (2007). Working memory, math performance, and math anxiety. *Psychonomic Bulletin & Review, 14*(2), 243–248. https://doi.org/10.3758/BF03194059

Ashcraft, M. H., Krause, J. A., & Hopko, D. R. (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). Paul H. Brookes Publishing Co.

Ashcraft, M. H., Kirk, E. P., & Hopko, D. (1998). On the cognitive consequences of mathematics anxiety. In C. Donlan (Ed.), *Studies in developmental psychology. The development of mathematical skills* (pp. 175–196). Psychology Press/Taylor & Francis (UK).

Bach, D. R., Flandin, G., Friston, K. J., & Dolan, R. J. (2009). Time-series analysis for rapid event-related skin conductance responses. *Journal of Neuroscience Methods, 184* (2), 224–234. https://doi.org/10.1016/j.jneumeth.2009.08.005

Barroso, C., Ganley, C. M., McGraw, A. L., Geer, E. A., Hart, S. A., & Daucourt, M. C. (2020). A meta-analysis of the relation between math anxiety and math achievement. *Psychological Bulletin*. https://doi.org/10.1037/bul0000307

Benedek, M., & Kaernbach, C. (2010a). A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods, 190*(1), 80–91. https://doi.org/10.1016/j.jneumeth.2010.04.028

Benedek, M., & Kaernbach, C. (2010b). Decomposition of skin conductance data by means of nonnegative deconvolution. *Psychophysiology, 47*, 647–658. https://doi.org/10.1111/j.1469-8986.2009.00972.x

Betz, N. E. (1978). Prevalence, distribution, and correlates of math anxiety in college students. *Journal of Counseling Psychology, 25*(5), 441–448. https://doi.org/10.1037/0022-0167.25.5.441

Bieg, M., Goetz, T., Wolter, I., & Hall, N. C. (2015). Gender stereotype endorsement differentially predicts girls' and boys' trait-state discrepancy in math anxiety. *Frontiers in Psychology, 6*(September), 1404. https://doi.org/10.3389/fpsyg.2015.01404

Boucsein, W. (1992). *Electrodermal activity*. Plenum University Press.

Braithwaite, J. J. J., Derrick, D., Watson, G., Jones, R., Rowe, M., Watson, D., … Mickey, R. (2013). A guide for analysing electrodermal activity (EDA) & skin conductance responses (SCRs) for psychological experiments. *Psychophysiology, 49* (1), 1017–1034. 10.1017.S0142716405050034.

Brown, T. A., Chorpita, B. F., & Barlow, D. H. (1998). Structural relationships among dimensions of the DSM-IV anxiety and mood disorders and dimensions of negative affect, positive affect, and autonomic arousal. *Journal of Abnormal Psychology, 107* (2), 179–192. https://doi.org/10.1037/0021-843X.107.2.179

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*(3), Article e0174418.

Carey, E., Hill, F., Devine, A., & Szucs, D. (2015). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Frontiers in Psychology, 6*(January), 1–6. https://doi.org/10.3389/fpsyg.2015.01987

Cargnelutti, E., Tomasetto, C., & Passolunghi, M. C. (2016). How is anxiety related to math performance in young students? A longitudinal study of Grade 2 to Grade 3 children. *Cognition and Emotion, 9931*(June), 1–10. https://doi.org/10.1080/02699931.2016.1147421

Cates, G. L., & Rhymer, K. N. (2003). Examining the relationship between mathematics anxiety and mathematics performance: An instructional hierarchy perspective. *Journal of Behavioral Education, 12*(1), 23–34. https://doi.org/10.1023/A:1022318321416

Codispoti, M., & Cesarei, A. D. E. (2007). Arousal and attention: Picture size and emotional reactions. *Psychophysiology, 44*, 680–686. https://doi.org/10.1111/j.1469-8986.2007.00545.x

Dawson, M. E., Schell, A. M., & Filion, D. L. (2007). The electrodermal system. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (pp. 159–181). Cambridge University Press.

DeCaro, M. S., Rotar, K. E., Kendra, M. S., & Beilock, S. L. (2010). Diagnosing and alleviating the impact of performance pressure on mathematical problem solving. *Quarterly Journal of Experimental Psychology (2006), 63*(8), 1619–1630. https://doi.org/10.1080/17470210903474286

Demirtaş, A. S., & Uygun, T. (2020). Attachment to parents and math anxiety in early adolescence: Hope and perceived school climate as mediators. *Current Psychology*. https://doi.org/10.1007/s12144-020-00964-1

Devine, A., Fawcett, K., Szűcs, D., & Dowker, A. (2012). Gender differences in mathematics anxiety and the relation to mathematics performance while controlling for test anxiety. *Behavioral and Brain Functions, 8*(1), 33. https://doi.org/10.1186/1744-9081-8-33

Devine, A., Hill, F., Carey, E., & Szűcs, D. (2018). Cognitive and emotional math problems largely dissociate: Prevalence of developmental dyscalculia and mathematics anxiety. *Journal of Educational Psychology, 110*(3), 431.

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*(4), 580–583. https://doi.org/10.1037/0022-0167.31.4.580

Dowker, A., Sarkar, A., & Looi, C. Y. (2016). Mathematics anxiety: What have we learned in 60 years? *Frontiers in Psychology, 7*(April), 508. https://doi.org/10.3389/fpsyg.2016.00508

Dreger, R. M., & Aiken, L. R. (1957). The identification of number anxiety in a college population. *Journal of Educational Psychology, 48*(6), 344–351. https://doi.org/10.1037/h0045894

Felmingham, K. L., Rennie, C., Manor, B., & Bryant, R.a. (2011). Eye tracking and physiological reactivity to threatening stimuli in posttraumatic stress disorder. *Journal of Anxiety Disorders, 25*(5), 668–673. https://doi.org/10.1016/j.janxdis.2011.02.010

Foley, A. E., Herts, J. B., Borgonovi, F., Guerriero, S., Levine, S. C., & Beilock, S. L. (2017). The math anxiety-performance link. *Current Directions in Psychological Science, 26*(1), 52–58. https://doi.org/10.1177/0963721416672463

Fowles, D. C., Christie, M. J., Edelberg, R., Grings, W. W., Lykken, D. T., & Venables, P. H. (1981). Committee report. Publication recommendations for electrodermal measurements. *Psychophysiology, 18*(3), 232–239. https://doi.org/10.1111/j.1469-8986.2012.01384.x

Frith, C. D., & Allen, H. A. (1983). The skin conductance orienting response as an index of attention. *Biological Psychology, 17*(1), 27–39.

Furner, J. M. (2019). Math anxiety trends: A poor math attitude can be a real disability. *Journal of Advances in Education Research, 4*(2), 75–85. https://doi.org/10.22606/jaer.2019.42004

Garibbo, M., Aylward, J., & Robinson, O. J. (2019). The impact of threat of shock-induced anxiety on the neural substrates of memory encoding and retrieval. *Social Cognitive and Affective Neuroscience, 14*(10), 1087–1096. https://doi.org/10.1093/scan/nsz080

Goetz, T., Bieg, M., Lüdtke, O., Pekrun, R., & Hall, N. C. (2013). Do girls really experience more anxiety in mathematics? *Psychological Science, 24*(10), 2079–2087. https://doi.org/10.1177/0956797613486989

Gunderson, E. A., Park, D., Maloney, E. A., Beilock, S. L., Levine, S. C., Gunderson, E. A., … Beilock, S. L. (2018). Reciprocal relations among motivational frameworks, math anxiety, and math achievement in early elementary school. *Journal of Cognition and Development, 19*(1), 21–46. https://doi.org/10.1080/15248372.2017.1421538

Gunderson, E.a., Ramirez, G., Levine, S. C., & Beilock, S. L. (2011). The role of parents and teachers in the development of gender-related math attitudes. *Sex Roles, 66* (3–4), 153–166. https://doi.org/10.1007/s11199-011-9996-2

Harari, R. R., Vukovic, R. K., & Bailey, S. P. (2013). Mathematics anxiety in young children: An exploratory study. *The Journal of Experimental Education, 81*(4), 538–555. https://doi.org/10.1080/00220973.2012.727888

Hart, S. A., & Ganley, C. M. (2019). The nature of math anxiety in adults: Prevalence and correlates. *Journal of Numerical Cognition, 5*(2), 122–139. https://doi.org/10.5964/jnc.v5i2.195

Hellhammer, D. H., Wüst, S., & Kudielka, B. M. (2009). Salivary cortisol as a biomarker in stress research. *Psychoneuroendocrinology, 34*(2), 163–171. https://doi.org/10.1016/j.psyneuen.2008.10.026

Hembree, R. (1990). The nature, effects, and relief of mathematics anxiety. *Journal for Research in Mathematics Education, 21*(1), 33–46.

Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., & Szucs, D. (2016). Math anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learning and Individual Differences, 48*, 45–53. https://doi.org/10.1016/j.lindif.2016.02.006

Hofmann, S. G., & Kim, H. J. (2006). Anxiety goes under the skin: Behavioral inhibition, anxiety, and autonomic arousal in speech-anxious males. *Personality and Individual Differences, 40*(7), 1441–1451. https://doi.org/10.1016/j.paid.2005.12.003

Huberty, C. J., & Olejnik, S. (2006). *Applied MANOVA and discriminant analysis* (Vol. 498). John Wiley & Sons.

Hunkin, H., King, D. L., & Zajac, I. T. (2019). Wearable devices as adjuncts in the treatment of anxiety-related symptoms: A narrative review of five device modalities and implications for clinical practice. *Clinical Psychology: Science and Practice, 26*(3), 1–12. https://doi.org/10.1111/cpsp.12290

Iffland, B., Sansen, L. M., Catani, C., & Neuner, F. (2014). Rapid heartbeat, but dry palms: Reactions of heart rate and skin conductance levels to social rejection. *Frontiers in Psychology, 5*, 956.

Justicia-Galiano, M. J., Martín-Puga, M. E., Linares, R., & Pelegrina, S. (2017). Math anxiety and math performance in children: The mediating roles of working memory and math self-concept. *British Journal of Educational Psychology, 87*(4), 573–589. https://doi.org/10.1111/bjep.12165

Kaufmann, L., & von Aster, M. (2012). The diagnosis and management of dyscalculia. *Deutsches Ärzteblatt International, 109*(45), 767–777. https://doi.org/10.3238/arztebl.2012.0767. quiz 778.

King, D., & Janiszewski, C. (2011). The sources and consequences of the fluent processing of numbers. *Journal of Marketing Research, 48*(2), 327–341. https://doi.org/10.1509/jmkr.48.2.327

Klados, M. A., Pandria, N., Micheloyannis, S., Margulies, D., & Bamidis, P. D. (2015). Math anxiety: Brain cortical network changes in anticipation of doing mathematics. *International Journal of Psychophysiology*, (October 2015)https://doi.org/10.1016/j.ijpsycho.2017.05.003

Kring, A. M., & Gordon, A. H. (1998). Sex differences in emotion: Expression, experience, and physiology. *Journal of Personality and Social Psychology, 74*(3), 686.

Kucian, K., Mccaskey, U., Tuura, R. O. G., & Von Aster, M. (2018). Neurostructural correlate of math anxiety in the brain of children. *Translational Psychiatry*. https://doi.org/10.1038/s41398-018-0320-6

Lader, M. (1967). Palmar skin conductance measures in anxiety and phobic states. *Journal of Psychosomatic Research, 11*, 271–281. https://doi.org/10.1016/0022-3999(67)90021-9

Landová, E., Peléšková, Š., Sedláčková, K., Janovcová, M., Polák, J., Rádlová, S., … Frynta, D. (2020). Venomous snakes elicit stronger fear than nonvenomous ones: Psychophysiological response to snake images. *PLoS ONE, 15*(8). https://doi.org/10.1371/journal.pone.0236999

Lau, J. Y., Eley, T. C., & Stevenson, J. (2006). Examining the state-trait anxiety relationship: A behavioural genetic approach. *Journal of Abnormal Child Psychology, 34*(1), 18–26.

Levy, H. E., Fares, L., & Rubinsten, O. (2021). Math anxiety affects females' vocational interests. *Journal of Experimental Child Psychology, 210*, Article 105214.

Lueken, U., Kruschwitz, J. D., Muehlhan, M., Siegert, J., Hoyer, J., & Wittchen, H. U. (2011). How specific is specific phobia? Different neural response patterns in two subtypes of specific phobia. *NeuroImage, 56*(1), 363–372. https://doi.org/10.1016/j.neuroimage.2011.02.015

Lukowski, S. L., DiTrapani, J., Jeon, M., Wang, Z., J.Schenker, V., Doran, M. M., … Petrill, S. A. (2019). Multidimensionality in the measurement of math-specific anxiety and its relationship with mathematical performance. *Learning and Individual Differences, 70*, 228–235. https://doi.org/10.1016/j.lindif.2016.07.007

Lyons, I. M., & Beilock, S. L. (2012). Mathematics anxiety: Separating the math from the anxiety. *Cerebral Cortex, 22*(9), 2102–2110. https://doi.org/10.1093/cercor/bhr289

Ma, X., & Xu, J. (2004). The causal ordering of mathematics anxiety and mathematics achievement: A longitudinal panel analysis. *Journal of Adolescence, 27*(2), 165–179. https://doi.org/10.1016/j.adolescence.2003.11.003

Malanchini, M., Rimfeld, K., Wang, Z., Petrill, S. A., Tucker-Drob, E. M., Plomin, R., & Kovas, Y. (2020). Genetic factors underlie the association between anxiety, attitudes and performance in mathematics. *Translational Psychiatry, 10*(1). https://doi.org/10.1038/s41398-020-0711-3

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*(8), 404–406. https://doi.org/10.1016/j.tics.2012.06.008

Maloney, E. A., & Retanal, F. (2020). Higher math anxious people have a lower need for cognition and are less reflective in their thinking. *Acta Psychologica, 202*(July 2019), Article 102939. https://doi.org/10.1016/j.actpsy.2019.102939

Mattarella-Micke, A., & Beilock, S. L. (2010). Situating math word problems: The story matters. *Psychonomic Bulletin & Review, 17*(1), 106–111. https://doi.org/10.3758/PBR.17.1.106

Miller, H., & Bichsel, J. (2004). Anxiety, working memory, gender, and math performance. *Personality and Individual Differences, 37*(3), 591–606. https://doi.org/10.1016/j.paid.2003.09.029

Moran, T. P. (2016). Anxiety and working memory capacity: A meta-analysis and narrative review. *Psychological Bulletin, 142*(8), 831–864. https://doi.org/10.1037/bul0000051

Muris, P., Hoeve, I., Meesters, C., & Mayer, B. (2004). Children's perception and interpretation of anxiety-related physical symptoms. *Journal of Behavior Therapy and Experimental Psychiatry, 35*(3), 233–244. https://doi.org/10.1016/j.jbtep.2004.03.008

Núñez-peña, M. I., & Bono, R. (2019). Academic anxieties: Which type contributes the most to low achievement in methodological courses? *Educational Psychology, 39*(6), 797–814. https://doi.org/10.1080/01443410.2019.1582756

Olsson-Collentine, A., van Assen, M. A. L. M., & Hartgerink, C. H. J. (2019). The prevalence of marginally significant results in psychology over time. *Psychological Science, 30*(4), 576–586. https://doi.org/10.1177/0956797619830326

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*(3), 371–399.

Orbach, L., Herzog, M., & Fritz, A. (2020). State- and trait-math anxiety and their relation to math performance in children: The role of core executive functions. *Cognition, 200* (March), Article 104271. https://doi.org/10.1016/j.cognition.2020.104271

Organization for Economic Co-operation and Development. (2013). *PISA 2012 results: Ready to learn: Students' engagement, drive and self-beliefs* (Vol. III). https://doi.org/10.1787/9789264201170-en. Paris, France.

Owens, M., Stevenson, J., Norgate, R., & Hadwin, J. A. (2008). Processing efficiency theory in children: Working memory as a mediator between trait anxiety and academic performance. *Anxiety, Stress and Coping, 21*(4), 417–430. https://doi.org/10.1080/10615800701847823

Palazova, M., Sommer, W., & Schacht, A. (2013). Interplay of emotional valence and concreteness in word processing: An event-related potential study with verbs. *Brain and Language, 125*(3), 264–271. https://doi.org/10.1016/j.bandl.2013.02.008

Pelegrina, S., Justicia-Galiano, M. J., Martín-Puga, M. E., & Linares, R. (2020). Math anxiety and working memory updating: Difficulties in retrieving numerical information from working memory. *Frontiers in Psychology, 11*(April), 1–10. https://doi.org/10.3389/fpsyg.2020.00669

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* (August), 100–107. https://doi.org/10.1016/j.bandc.2017.08.004

Pizzie, R. G., & Kraemer, D. J. M. (2019). The Academic Anxiety Inventory: Evidence for dissociable patterns of anxiety related to math and other sources of academic stress. *Frontiers in Psychology, 9*(JAN), 1–20. https://doi.org/10.3389/fpsyg.2018.02684

Plake, B. S., & Parker, C. S. (1982). The development and validation of a revised version of the Mathematics Anxiety Rating Scale. *Educational and Psychological Measurement, 42*(2), 551–557.

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*(3), 410–416. https://doi.org/10.1016/j.biopsycho.2010.08.015

Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review, 78*(5), 391.

Qu, Z., Chen, J., Li, B., Tan, J., Zhang, D., & Zhang, Y. (2020). Measurement of high-school students' trait math anxiety using neurophysiological recordings during math exam. *IEEE Access, 8*, 57460–57471. https://doi.org/10.1109/ACCESS.2020.2982198

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2013). Math anxiety, working memory, and math achievement in early elementary school. *Journal of Cognition and Development, 14*(2), 187–202.

Richardson, F. C., & Suinn, R. M. (1972). The Mathematics Anxiety Rating Scale: Psychometric data. *Journal of Counseling Psychology, 19*(6), 551–554. https://doi.org/10.1037/h0033456

Rodríguez-Arce, J., Lara-Flores, L., Portillo-Rodríguez, O., & Martínez-Méndez, R. (2020). Towards an anxiety and stress recognition system for academic environments based on physiological features. *Computer Methods and Programs in Biomedicine, 190*. https://doi.org/10.1016/j.cmpb.2020.105408

Roos, A. L., Goetz, T., Voracek, M., Krannich, M., Bieg, M., Jarrell, A., & Pekrun, R. (2020). Test anxiety and physiological arousal: A systematic review and meta-analysis. *Educational Psychology Review*. https://doi.org/10.1007/s10648-020-09543-z

Roth, W. (2005). Physiological markers for anxiety: Panic disorder and phobias. *International Journal of Psychophysiology, 58*(2-3 SPEC. ISS), 190–198. https://doi.org/10.1016/j.ijpsycho.2005.01.015

Roth, W. T., Ehlers, A., Taylor, C. B., Margraf, J., & Agras, W. S. (1990). Skin conductance habituation in panic disorder patients. *Biological Psychiatry, 27*(11), 1231–1243. https://doi.org/10.1016/0006-3223(90)90421-W

Rubinsten, O., & Tannock, R. (2010). Mathematics anxiety in children with developmental dyscalculia. *Behavioral and Brain Functions, 6*, 46. https://doi.org/10.1186/1744-9081-6-46

Rubinsten, O., Bialik, N., & Solar, Y. (2012). Exploring the relationship between math anxiety and gender through implicit measurement. *Frontiers in Human Neuroscience, 6*(October), 279. https://doi.org/10.3389/fnhum.2012.00279

Rubinsten, O., Eidlin, H., Wohl, H., & Akibli, O. (2015). Attentional bias in math anxiety. *Frontiers in Psychology, 6*(October), 1–9. https://doi.org/10.3389/fpsyg.2015.01539

Rubinsten, O., Eidlin-Levy, H., & Daches-Cohen, L. (2019). Probing the nature of deficits in math anxiety. In I. C. Mammarella, S. Caviola, & A. Dowker (Eds.), *Mathematics anxiety: What is known, and what is still missing* (p. 156). Routledge.

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*, 291.

Sheppes, G., Catran, E., & Meiran, N. (2009). Reappraisal (but not distraction) is going to make you sweat: Physiological evidence for self-control effort. *International Journal of Psychophysiology, 71*(2), 91–96. https://doi.org/10.1016/j.ijpsycho.2008.06.006

Siegel, E. H., Sands, M. K., Van den Noortgate, W., Condon, P., Chang, Y., Dy, J., … Barrett, L. F. (2018). Emotion fingerprints or emotion populations? A meta-analytic investigation of autonomic features of emotion categories. *Psychological Bulletin, 144* (4), 343–393. https://doi.org/10.1037/bul0000128

Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A. J., Ehlis, A. C., & Nuerk, H. C. (2019). Math anxiety in combination with low visuospatial memory impairs math learning in children. *Frontiers in Psychology, 10*(January), 1–10. https://doi.org/10.3389/fpsyg.2019.00089

Spielberger, C. D. (1966). Theory and research on anxiety. *Anxiety and behavior, 1*(3).

Spielberger, C. D. (1972). *Anxiety: Current trends in research*. Academic Press.

Spielberger, C. D., Gorsuch, R. L., Lushene, R., Vagg, P. R., & Jacobs, G. A. (1983). *Manual for the state-trait anxiety inventory*. Consulting Psychologists Press.

Stemmler, G., Heldmann, M., Pauls, C. A., & Scherer, T. (2001). Constraints for emotion specificity in fear and anger: The context counts. *Psychophysiology, 38*(2), 275–291. https://doi.org/10.1017/S0048577201991668

Stevens, J. P. (2002). *Applied multivariate statistics for the social sciences*. Lawrence Erblaum.

Stone, M. H. (2010). History of anxiety disorders. In D. J. Stein, E. Hollander, & B. O. Rothbaum (Eds.), *Textbook of anxiety disorders* (pp. 3–15). American Psychiatric Publishing, Inc.

Strohmaier, A. R., Schiepe-Tiska, A., & Reiss, K. M. (2020). A comparison of self-reports and electrodermal activity as indicators of mathematics state anxiety. An application of the control-value theory. *Frontline Learning Research, 8*(1), 16–32.

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*(OCT). https://doi.org/10.3389/fpsyg.2015.01577

Supekar, K., Iuculano, T., Chen, L., & Menon, V. (2015). Remediation of childhood math anxiety and associated neural circuits through cognitive tutoring. *Journal of Neuroscience, 35*(36), 12574–12583. https://doi.org/10.1523/JNEUROSCI.0786-15.2015

Szczygieł, M. (2020). Gender, general anxiety, math anxiety and math achievement in early school-age children. *Issues in Educational Research, 30*(3), 1126–1142.

Trost, Z., Jones, A., Guck, A., Vervoort, T., Kowalsky, J. M., & France, C. R. (2017). Initial validation of a virtual blood draw exposure paradigm for fear of blood and needles. *Journal of Anxiety Disorders, 51*(August), 65–71. https://doi.org/10.1016/j.janxdis.2017.03.002

Vandekerckhove, J., Rouder, J. N., & Kruschke, J. K. (2018). Editorial: Bayesian methods for advancing psychological science. *Psychonomic Bulletin and Review, 25*(1), 1–4. https://doi.org/10.3758/s13423-018-1443-8

Venables, P. H., & Mitchell, D. A. (1996). The effects of age, sex and time of testing on skin conductance activity. *Biological Psychology, 43*(2), 87–101. https://doi.org/10.1016/0301-0511(96)05183-6

Vianello, M., Schnabel, K., Sriram, N., & Nosek, B. (2013). Gender differences in implicit and explicit personality traits. *Personality and Individual Differences, 55*(8), 994–999. https://doi.org/10.1016/j.paid.2013.08.008

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., … Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin and Review, 25*, 58–76.

Wang, Z., Hart, S. A., Kovas, Y., Lukowski, S., Soden, B., Thompson, L. A., … Petrill, S. A. (2014). Who is afraid of math? Two sources of genetic variance for mathematical anxiety. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, 1–9. https://doi.org/10.1111/jcpp.12224

Wang, Z., Lukowski, S. L., Hart, S. A., Lyons, I. M., Thompson, L. A., Kovas, Y., … Petrill, S. A. (2015). Is math anxiety always bad for math learning? The role of math motivation. *Psychological Science, 26*(12), 1863–1876. https://doi.org/10.1177/0956797615602471

Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's statement on p-values: Context, process, and purpose. *American Statistician, 70*, 129–133.

Watson, D. R., Garfinkel, S. N., Van Praag, C. G., Willmott, D., Wong, K., Meeten, F., & Critchley, H. D. (2019). Computerized exposure therapy for spider phobia: Effects of cardiac timing and interoceptive ability on subjective and behavioral outcomes. *Psychosomatic Medicine, 81*(1), 90–99. https://doi.org/10.1097/PSY.0000000000000646

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III tests of achievement*. Riverside Publishing.

Wu, S. S., Barth, M., Amin, H., Malcarne, V., & Menon, V. (2012). Math anxiety in second and third graders and its relation to mathematics achievement. *Frontiers in Psychology, 3*(June), 162. https://doi.org/10.3389/fpsyg.2012.00162

Xie, F., Xin, Z., Chen, X., & Zhang, L. (2019). Gender difference of Chinese high school students' math anxiety: The effects of self-esteem, test anxiety and general anxiety. *Sex Roles, 81*(3–4), 235–244. https://doi.org/10.1007/s11199-018-0982-9

Young, C. B., Wu, S. S., & Menon, V. (2012). The neurodevelopmental basis of math anxiety. *Psychological Science, 23*(5), 492–501. https://doi.org/10.1177/0956797611429134

Zakaria, E., & Nordin, N. M. (2008). The effects of mathematics anxiety on matriculation students as related to motivation and achievement. *Eurasia Journal of Mathematics, Science and Technology Education, 4*(1), 27–30. https://doi.org/10.12973/ejmste/75303

Zettle, R. D., & Raines, S. J. (2000). The relationship of trait and test anxiety with mathematics anxiety. *College Student Journal, 34*(2), 246–259.

Zhang, J., Zhao, N., & Kong, Q. P. (2019). The relationship between math anxiety and math performance: A meta-analytic investigation. *Frontiers in Psychology, 10* (August), 1–17. https://doi.org/10.3389/fpsyg.2019.01613

Zhang, X., Dong, Y., & Zhou, R. (2018). Examination stress results in attentional bias and altered neural reactivity in test-anxious individuals. *Neural Plasticity, 2018*. https://doi.org/10.1155/2018/3281040