THE UNIVERSITY OF CHICAGO

CALCULATED AVOIDANCE: THE ROLE OF EFFORT-BASED VALUATIONS IN THE RELATION BETWEEN MATH ANXIETY AND MATH AVOIDANCE

A DISSERTATION SUBMITTED TO

THE FACULTY OF THE DIVISION OF THE SOCIAL SCIENCES

IN CANDIDACY FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

DEPARTMENT OF PSYCHOLOGY

BY

JALISHA BRAXTON JENIFER

CHICAGO, ILLINOIS

MARCH 2021

This dissertation is dedicated to Georgiana Rose Simpson, UChicago Ph.D. 1921

Thank you for being first. Because of you I could.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would first like to thank the members of my dissertation committee: to my advisors, Susan Levine and Sian Beilock, thank you for all of your support and guidance throughout my graduate school career. I've learned so much from having the two of you as role models and mentors and am excited to continue working together in the future. Marc Berman, thank you for all of your guidance and feedback on the many projects that we've worked on together, including the ones in this dissertation- you've contributed significantly to my understanding of statistics and experimental design, both of which have been critical in my development as a researcher and scholar. Last, but not least, Lindsey Richland, I am beyond grateful that you agreed to join my committee in the middle of the unfathomable coronavirus pandemic. Thank you for adding on another commitment in the midst of such uncertain times- your feedback and enthusiasm helped me see the broader impacts of my work and renewed my hope for a future in academia.

I would also like to thank all of the funders that have supported this research and my graduate studies as a whole: the National Science Foundation, the Institute of Education Sciences, the Norman Anderson Fund, and the University of Chicago Social Sciences Division. Thank you for believing in me and my potential. I'm also incredibly grateful for all of the staff members at the University of Chicago, especially those in the Psychology department (Ray Weathers, Meyosha Smiley, Mimi Maduff, Shomari Tate, Kristi Schonwald, Jodi Khan, and especially Laura Judson): thank you for lending a listening ear and supporting me in all the ways that are often unseen or unacknowledged.

I'm also grateful for the support given to me by various graduate student communities, including the Psychology Graduate Student Organization (especially the Diversity & Inclusion Committee), the Institute of Education Sciences fellows, and the Chicago Center for Teaching fellows. Thank you all for your individual and collective encouragement, invaluable insight, and constructive advice, all of which made even the most challenging moments worthwhile. I'd like to give special thanks to the members of my UChicagoGrad Structured Writing Accountability Group: so much of my dissertation was written during our virtual writing sessions as a result of your encouragement and kindness. Thank you so much for your consistent support. I am also particularly indebted to Michelle Hurst, Cristina Carrazza, Nancy Pantoja, Maddy Oswald, and Jake Butts for providing a sense of community and structure throughout grad school, especially as I pushed to finish everything in the middle of the pandemic. I owe you my sanity. Nancy & Maddy, thank you for also being the best officemates imaginable; I'm so grateful that I had both of you through all of the highs and lows that come with day-to-day grad school life. I would also like to thank to the former members of the Beilock lab, especially Marjorie Schaeffer, Julianne Herts, Kyoung whan Choe and Chris Rozek- thank you all for showing me the ropes of academia and helping me find my place in it.

Of course, none of this would even be possible without the support of my family, friends, teachers and mentors who have been my support system since the beginning of it all. Thank you for encouraging me to follow my dreams (and for bringing me back to reality when I lost myself in a book or two). Mom, thank you for being my toughest critic and my biggest supporter. This dissertation is a manifestation of the passion for education and learning you instilled in me, for which I will be forever grateful. To my husband, Sam, thank you for sticking with me through everything and for being my home away from home. I'm so fortunate to have you as a life partner (and as a permanent pilot participant for all of my future research studies).

Finally, and most importantly, I'd like to thank my Lord and Savior Jesus Christ, whose unwavering love humbles me and keeps me grounded in everything I do. Thank You for choosing me as the vessel through which this work is shared with the world.

ABSTRACT

Individuals who experience math anxiety are often characterized as math avoidant, with highly math-anxious students opting into fewer STEM courses and careers than their less-anxious peers (Hembree, 1990). These avoidance behaviors have been theorized to mediate the relation between math anxiety and performance, as students who avoid math are likely to have less exposure to and practice with mathematical concepts (Carey et al., 2016). However, most of the existing literature focuses on global avoidance behaviors where math can be completely avoided; as a result, little is known about how math-avoidant tendencies impact decision-making in situations where it is impossible to completely avoid math, such as when math-anxious students are enrolled in a math course.

In an effort to fill this gap in the literature, I conducted a series of experiments that investigated the relation between math anxiety and math avoidance in contexts where math engagement is required. Using expectancy-value-cost models of achievement motivation as a foundation, I developed a theory of math-specific effort avoidance which posits that math avoidance behaviors emerge for math-anxious individuals when they perceive the costs of effortful math engagement to outweigh its benefits. In Study 1, I tested my theory by evaluating the choice behavior of math-anxious individuals using a novel effort-based decision-making task. I found evidence in support of the effort-avoidance theory, as math-anxious individuals exhibited a tendency to select easier, low-reward options over harder, high-reward options when choosing math problems to solve. In Study 2, I explored the real-world consequences of math-specific effort avoidance by investigating whether math anxiety relates to students' use of effortful study strategies when preparing for a mathematics exam. I found that math anxiety was associated with the avoidance of effortful problem-solving during exam preparation, and that this effort

avoidance behavior partially mediated the association between math anxiety and exam performance. Finally, in Study 3 I investigated the utility of effortful math engagement for increasing the math performance of math-anxious individuals. The results from this study suggest that the utility of effortful problem-solving during exam preparation depends on practice problem accuracy, and that intervening on accuracy is important for improving the math performance of math-anxious students. Together, the findings from the current dissertation provide support for the theory of math-specific effort avoidance and highlight considerations for improving the math performance of math-anxious individuals.

INTRODUCTION

For decades, social scientists have strived to uncover the determinants of academic success. One such determinant found to significantly impact educational outcomes within the domain of mathematics is math anxiety (Hembree, 1990; Ma, 1999). Defined as feelings of tension, apprehension, or fear about mathematics (Ashcraft, 2002; Richardson & Suinn, 1972), math anxiety is distinct from other forms of anxiety and has been shown to correlate strongly with poor math performance for students around the world (Foley et al., 2017).

Multiple theories have been proposed to explain how math anxiety influences math learning and performance (for reviews, see Carey et al., 2016; Ramirez et al., 2018). Although one of the most prominent theories asserts that math anxiety limits the availability of working memory resources needed for problem-solving (Ashcraft & Kirk, 2001; Beilock & Carr, 2005; Ramirez & Beilock, 2011), another suggests that math-anxious students perform worse in math because they are math avoidant (Richardson & Suinn, 1972; Hembree, 1990). These avoidance behaviors are thought to limit students' practice of math concepts, reducing their exposure to math in ways that negatively impact their future math outcomes (Carey et al., 2016; Ramirez et al., 2018).

Despite the early emergence of the avoidance theory in the literature, however, there is little data exploring how, why, and when math-anxious individuals actually engage in math avoidance behaviors. Additionally, most of the limited literature on this topic focuses on situations where math can be completely avoided, such as the avoidance of math courses and careers (Hembree, 1990; LeFerve et al., 1992). As a result, little is known about how math-avoidant tendencies manifest and impact decision-making in situations where it is impossible to completely avoid math, such as when math-anxious students are enrolled in a math course.

Gaining a full understanding of this process may be particularly useful for understanding whether math-anxious individuals make course-specific decisions that have negative consequences for their math outcomes.

The aim of this dissertation, then, is to gain insight about the relation between math anxiety and math avoidance within a mandatory math context. In this first chapter, I review the existing literature on the relation between math anxiety and math avoidance. Insight gained from the review will then be used to develop a theory predicting the relation between math anxiety and math-specific avoidance behaviors. In the remaining chapters, I will describe the results of three experiments designed to test the proposed theory.

Math Avoidance as "Global Avoidance"

The idea that math anxiety leads to math avoidance emerged as early as 1972, when Richardson and Suinn developed the Math Anxiety Rating Scale (MARS) and posited that "mathematics anxiety may prevent a student from passing fundamental mathematics courses or prevent his pursuing advanced courses in mathematics or the sciences" (Richardson & Suinn, 1972). This conceptualization of math avoidance led the math anxiety literature to focus on what Ashcraft and Faust refer to as *global avoidance*: "the tendency of math-anxious individuals to avoid situations that are math intensive, such as elective coursework in secondary and postsecondary education" (Ashcraft & Faust, 1994). Despite the early emergence of this theory in the literature, however, no articles exist that delineate the history of this theorization or provide a thorough summary of the findings from the literature on this topic. To address these shortcomings, an extensive description will be provided for the research described below.

The first known work to test the relation between math anxiety and global math avoidance appears to come from Brush in 1980. In the study, which aimed to validate the

MARS, undergraduate students were recruited to complete the MARS as well as a questionnaire on their background in mathematics. The study found an inverse relationship between MARS scores, the number of years students took high school mathematics courses, and the number of terms students were enrolled in Calculus. Additionally, the study found differences in math anxiety across different majors: Physical Science majors showed evidence of being the least anxious about quantitative situations, followed by Social Science majors, and then Humanities majors. The authors took these findings as evidence that math anxiety is associated with the avoidance of math-related courses as well as math-intensive majors.

Following the publication of the study by Brush, additional studies began to emerge using college major and math course enrollment as proxies for math avoidance behavior. In a study by Kelly and Tomhave (1985), groups of students were first identified as "math avoidant" based on their mathematics background: freshman who hadn't taken any college-prep math courses, seniors who hadn't taken any college math courses, freshman who were enrolled in college algebra (and thus had minimal exposure to college-level math), a group of students who were enrolled in a workshop for those with math anxiety, and elementary education majors (most of whom hadn't taken math higher than college algebra). The researchers then measured the math anxiety of these students using the MARS to determine whether math-avoidant students are also math anxious. The study found that the mean math anxiety scores for the elementary education majors and the students in the math anxiety workshop were significantly higher than any of the other math avoidant groups of students. These findings provide support for the math avoidance theory while also suggesting that not all math avoiders are math anxious.

While many early studies in the literature operationalized math avoidance as the avoidance of math courses and careers, a 1992 study by LeFerve and colleagues expanded the literature on math avoidance by utilizing a scale item to capture math avoidance tendencies. In their study, the math anxiety and avoidance levels of 126 introductory psychology undergraduates were measured by asking how often they find that situations involving math make them nervous (from 1 "almost always" to 7 "almost never") and whether they actively avoid situations involving math (from 1 "always try to avoid math" to 7 "never try to avoid math"). The study found a strong correlation between math anxiety and math avoidance using the single-item measures of both variables, which the authors interpreted as showing that individuals who are anxious about math control their anxiety by avoiding mathematics. Using a composite of their math anxiety and math avoidance variables (which they referred to as "math affect"), the researchers also found that students who expressed more negative affect towards math took fewer math classes in high school and were less likely to be enrolled in majors with large numbers of mathematical prerequisites and degree requirements. Additionally, the study found that math affect and attitudes accounted for an additional 16% of variance in major choice after student age, fluency, and experience were accounted for. These findings provide additional evidence for the relation between math anxiety and math avoidance and provide validation for the use of scale items to capture math avoidance tendencies.

Although research on the relation between math anxiety and math avoidance first emerged in the 1980's, the most commonly cited evidence from the literature comes from a meta-analysis conducted by Hembree in 1990. The meta-analysis, which was conducted on 151 studies from the math anxiety literature, supported the results of previous studies with its finding that high-anxious students take fewer high school mathematics courses and show less intention in high school and college to take more mathematics. Additionally, the meta-analysis found that while females display higher levels of math anxiety than males, the link between math anxiety and math avoidance is more strongly linked in males compared to females. This finding led to a wave of additional research investigating the role of gender in the development of math anxiety, though little work has investigated the gender-avoidance link explicitly.

In sum, research on global math avoidance behavior has been relatively consistent in finding a relation between math anxiety and the avoidance of math-related courses and careers. However, this work is primarily correlational, with most studies using course enrollment and major selection as proxies for avoidance behavior. Nonetheless, a few researchers have attempted to test the relation between math anxiety and math avoidance experimentally-
I cover this research in the next section.

Math Avoidance as "Local Avoidance"

While most of the studies in the math anxiety literature describe math avoidance as a global avoidance of math-related situations, a limited number of studies also suggest that math anxiety can lead to math avoidance at the level of cognitive processing. This type of avoidance, termed "local avoidance" by Ashcraft and Faust (1994), has been conceptualized as the avoidance of cognitive involvement and attention during a math task (Faust, 1992; Ashcraft & Faust, 1994; Faust, Ashcraft, & Fleck, 1996). This conceptualization has led researchers to operationalize local math avoidance in a variety of ways within the literature.

In 1984, Dew, Galassi and Galassi explored what can be considered local math avoidance by testing the effect of math anxiety on the avoidance of difficult problem-solving. In the study, undergraduate students were given a set of math problems and were instructed to solve the problems "quickly but accurately" within a 15-minute time limit. Critically, students were told that the problems were a test of their math ability, and that they could complete the problems in any order. Students were also told that more credit would be received for the more difficult problems and that the difficulty level decreased as the problem set progressed (although problem difficulty actually remained approximately constant throughout the set). Math avoidance was operationalized in the study as the avoidance of difficult problems and was scored on a 4-point scale based on the number of problems students skipped and completed out of sequence. The study found that math anxiety was unrelated to problem completion order across. However, the authors also found that while 74% of the students solved the problems in order, only 18% of participants reported solving the most difficult items first. Thus, the authors state that the students in the study may not have fully comprehended their difficulty manipulation and conclude that completion order may not have been a satisfactory measure of avoidance behavior during problem-solving.

In 1994, Ashcraft and Faust explicitly theorized about the existence of localized math avoidance behaviors after noticing that highly math anxious students seemed to engage in speed-accuracy tradeoffs during problem-solving. In their study, undergraduate students were presented with completed arithmetic equations and were asked to report whether the equation solution was true or false. Highly math-anxious students were generally found to have similar reaction times to those of their less-anxious peers, but made significantly more incorrect responses or "errors" about the accuracy of the problem solution. Similar results were found in a follow-up study by Faust and colleagues in 1996 (Faust, Ashcraft, & Fleck, 1996). The authors interpreted this pattern of quick but incorrect responding as potentially reflecting participants' desire to "dispose of the task as soon as possible" (p. 121). Linking their findings to those found by Faust (1992) in which highly-math anxious individuals demonstrated reduced arousal during difficult problem solving, the authors posit that the "physiological costs" of engaging with math might lead highly math anxious individuals to avoid math stimuli.

Additional research by Morsanyi and colleagues (2014) supports the conceptualization of localized math avoidance as the avoidance of cognitive involvement and attention. The study recruited college students with varying levels of math anxiety to complete the cognitive reflection test (CRT), a measure of an individual's ability to inhibit intuitive responses (Frederick, 2005). Their study found that higher levels of math anxiety were associated with decreased cognitive reflection, suggesting avoidance at the level of cognitive processing. A study by Maloney and Retanal in 2020 replicated the findings of Morsanyi and colleagues while also discovering a significant negative relation between math anxiety and individuals' need for cognition (Cacioppo & Petty, 1982). These findings suggest that individuals who experience math anxiety may be less likely to engage in and enjoy effortful cognitive processing, providing further support for local avoidance theories.

Neuroimaging studies have also been conducted that explore the relation between math anxiety and math avoidance at the local level. In a study by Lyons and Beilock (2012), higher levels of math anxiety were linked to increased activation of cortices associated with threat detection and the experience of pain when anticipating an upcoming math task. Similarly, a neuroimaging study by Pizzie and Kraemer (2017) sought to investigate the relation between math anxiety and "moment-to-moment" reactions to viewing math stimuli. The study found increased amygdala responses in participants as they viewed math problems. Additionally, the study found brain patterns similar to those of vigilance and avoidance observed in specific phobia during math problem solving. The authors interpret these findings as evidence of attentional disengagement by highly math anxious individuals while engaging in math tasks.

In sum, there exists a small but succinct body of work within the math anxiety literature on math avoidance at the local level. This work suggests that math anxiety results in the avoidance of cognitive involvement and attention during cognitive processing. However, while much of the work on local math avoidance is experimental, the studies focus primarily on avoidance behavior *during* problem-solving and therefore say little about how math anxiety might impact decisions made *about* problem-solving within a math context. Understanding such localized decision-making is nonetheless important, as the decisions individual's make within math contexts can play a significant role in determining their math outcomes. Thus, in the next section of this chapter, we bridge the findings from the global and local math avoidance literatures with literature on achievement motivation to theorize how math anxiety might impact localized decision-making outcomes.

Math Avoidance as "Effort Avoidance"

Despite the many studies linking math anxiety to math avoidance behaviors, little is known about how math-anxious individuals reason about math-related choices within a math context. In order to gain insight about this topic, an understanding of the mechanisms underlying the relation between math anxiety and math avoidance is needed. However, very few studies investigate these mechanisms within the literature.

One of the only studies known to explore the mechanisms underlying the relation between math anxiety and math avoidance was conducted by Meece, Wigfield, and Eccles in 1990. Grounded in the expectancy-value model of achievement motivation, the study sought to explore how motivational variables interacted with the link between math anxiety and math avoidance. They found that higher levels of math anxiety were associated with less intent to enroll in math courses, but that this relation was completely mediated by students' value perceptions for math. This finding, though rarely referenced in the math anxiety literature, suggests that the relation between math anxiety and math avoidance may be completely dependent on how students reason about the value of the subject.

The findings from the study by Meece and colleagues suggest that expectancy-value models of achievement motivation might be particularly useful for gaining further insight about how math-anxious individuals make decisions in a math context. These models posit that academic behaviors are motivated both by individuals' level of expected success in a task as well as their value for engaging in the task (Eccles et al., 1983). Additionally, these models specifically theorize that decisions to avoid math-related courses and careers may be driven by individual's perceptions of how costly it is to engage mathematical tasks (Meece et al., 1982). Defined as students' perceptions regarding the negative consequences of engaging in a task, cost was initially theorized as a sub-component of value in these models and was suggested to consist of three elements: the amount of effort needed to be successful in a task, the time lost to engage in other valued activities, and the negative psychological states that result from failing or struggling with a task (Eccles et al., 1983; Barron & Hulleman, 2015). Despite this explicit theorization, however, cost perception and its various elements have only recently received attention in the achievement motivation literature.

In 2015, Barron and Hulleman put forth a theory suggesting that cost perceptions independently contribute to individuals' choice behaviors and should therefore be considered separate from value judgements. This theory, referred to as the expectancy-value-cost model of achievement motivation, suggests that students' cost perceptions may actually moderate their value perceptions of a task, and may therefore be important to measure as an independent construct. In support of this theory, scales developed to incorporate cost as a separate component of expectancy-value models have found validity evidence in support of the construct (Flake et al., 2015; Kosovich et al., 2015). Additionally, a recent study by Jiang and colleagues found that students' cost perceptions predicted their adoption of avoidance goals, negative classroom affect, maladaptive academic outcomes, as well as their exam scores (Jiang, Rosenzweig, & Gaspard, 2018). Cost perceptions may therefore be a critical mechanism to consider when exploring individual's academic choice behaviors.

Although cost has been suggested to consist of three primary elements, perceptions of task-related effort may be particularly important for understanding how individuals make choice behaviors. Described as students' perceptions of how much effort is needed to be successful in a task, effort perceptions have been described in the achievement motivation literature as a key driver of perceptions of costs (Parsons et al., 1982). Eccles and colleagues specifically hypothesized that cost perceptions would be high if the amount of effort required for a task is not perceived to be worth the benefit (Eccles et al., 1983). This viewpoint of effort-based costs is adopted in the current work.

Based on my review of the math anxiety literature and the related literature on expectancy-value models of achievement motivation, I theorize that math avoidance behaviors will emerge for individuals within a math context when the costs of effortful math engagement are perceived to outweigh the benefits, and that this perception will depend on individual differences in math anxiety. Thus, I hypothesize that higher levels of math anxiety will be associated with the avoidance of effortful engagement for individuals within a math context. These ideas make up the proposed theory of math-specific effort avoidance, which is explicitly tested and reported on in the subsequent chapters.

Overview of the Current Research

To test the proposed theory of math-specific effort avoidance, I conducted a series of experiments that investigated the relation between math anxiety and math avoidance in contexts where math engagement was required. Study 1 empirically tests the relation between math anxiety and math avoidance through the utilization of an effort-based decision-making task that measures one's tendency to select easier, low-reward problems over harder, high-reward problems in both a math and non-math context. Study 2 investigates math anxiety as a mediator in the relation between math anxiety and math performance within a classroom context as students report how they plan to allocate their study time when preparing for an upcoming math exam. Finally, Study 3 investigates the utility of effortful study strategy engagement for math-anxious individuals. Together, this body of work aims to broaden the current literature's understanding of math avoidance behaviors and contribute to the growing body of knowledge on how to improve the math performance of individuals who experience math anxiety.

STUDY 1: TESTING THE RELATION BETWEEN MATH ANXIETY AND MATH-SPECIFIC EFFORT AVOIDANCE

As previously stated, the proposed theory of math-specific effort avoidance makes predictions about how math anxiety might impact choice behavior for individuals within a math context. Specifically, the theory posits that math anxiety leads individuals to view the costs of effortful math engagement as outweighing the benefits, ultimately causing individuals to engage in math avoidance behavior. However, while this theory is motivated by previous findings from the math anxiety and achievement motivation literature, empirical evidence is needed to substantiate its claims. Therefore, the primary aim of Study 1 is to empirically test the proposed theory.

Essential to testing the theory of math-specific effort-avoidance is the need for an empirical task that measures effort-based decision-making. For this, I turn to the literature on cognitive effort more generally, where paradigms known as "dual alternative tasks" are frequently used to quantify human motivational patterns (Chong et al., 2016; Shenhav et al., 2017). In these tasks, individuals choose whether to engage in a high-effort/high-reward task or a low-effort/low-reward task across a series of trials (Treadway et al., 2012). Greater selection of the high-effort/high-reward option is viewed as an indicator of more motivation (and therefore less effort avoidance). Some variations of dual-alternative tasks also employ "staircase" reward structures in which the value associated with the low-effort option is held constant while the value of the high-effort option varies across trials (Westbrook et al., 2013). This method provides insight into individualized effort-reward thresholds, as it showcases how high a reward must be set in order to motivate an individual to engage in a high-effort task.

Another major strength of dual alternative tasks is their ability to separate an individual's effort-based choices from their actual effort expenditure. Most tasks consist of a "choice" phase in which participants select their effort/reward preference as well as an "execution" phase during which the task is carried out. This design provides targeted information about how people reason about costs and benefits of effort engagement in the choice phase while providing additional information about their ability to perform the task in the execution phase. However, since task-related rewards are typically contingent upon successful task execution, most dual alternative paradigms also employ some mechanism to control for differences in participant ability level (Chong et al., 2016). These control mechanisms ensure that participants' choice behavior isn't influenced by their likelihood of successfully completing the task, which is critical for obtaining an unbiased measure of choice behavior.

In the current experiment, the principles and methods of dual-alternative tasks are utilized in a novel effort-based decision-making paradigm designed to measure math avoidance tendencies. In the task, referred to as the Choose-And-Solve-Task (CAST), participants chose whether to solve a low-effort or high-effort math problem across a series of trials. The task also included non-math trials in which participants chose whether to solve a low-effort and high-effort word-spelling problem. Critically, a staircase reward ratio was employed in the task so that low-effort problems were valued at two cents in every trial, while high-effort problems fluctuated between five different value levels (2, 3, 4, 5, and 6 cents) across trials. Additionally, an adaptive difficulty manipulation was employed for each problem type to control for differences in participant math and word-spelling ability.

Based on the proposed theory of math-specific effort avoidance, we hypothesized that individuals with higher levels of math anxiety would be more likely to perceive the costs of effortful math engagement as outweighing the benefits, and would therefore choose to solve the low-effort/low-reward math problems over the high-effort/high-reward math problems, even when the high-effort problem held a significantly greater reward value. We also hypothesized that the effect of math anxiety on effort-based decision-making would be specific to the domain of math and would therefore have no influence how individuals with higher levels of math anxiety reasoned about effort on the non-math trials.

The results from this study were published in Science Advances with a Creative Commons BY license; parts of the publication (Materials and Methods, Results, Discussion) are reproduced with adaptations below with permission from the publisher.[1] Links to our preregistered hypotheses, open data materials, and supplementary materials are provided in Appendix A.

Materials and Methods

Participants

All studies were approved by the Social and Behavioral Sciences Institutional Review Board of the University of Chicago (IRB#16-0639). Participants were recruited via TurkPrime to complete the studies online via Amazon Mechanical Turk (see Supplementary Materials for details) and provided informed consent prior to participation. They were compensated with a combination of base amount and a performance-based bonus in the CAST (described in the *Experimental Procedure* section). We limited the analyses to those who passed the problem-solving accuracy criteria (described in the *Choose-And-Solve Task* section). Outliers were not excluded.

---

[1] From K. W. Choe, J. B. Jenifer, C. S. Rozek, M. G. Berman, S. L. Beilock, Calculated avoidance: Math anxiety predicts math avoidance in effort-based decision-making. *Sci. Adv.* **5**, eaay1062 (2019). Reproduced with minor adaptations with permission from AAAS.

Study 1.1 was exploratory; a desired sample size of 194 was set to detect an expected correlation of .2 with 80% power at a 5% significance level. Due to computer errors 154 participants completed Study 1.1, and we report the results from 142 participants (age: M = 37.4, SD = 10.1, range = 21-66; Sex: 56 females, 77 males, 9 other/not-identified/lost). Study 1.1R was conducted to measure test-retest reliability of the CAST; 103 out of the 142 participants performed the CAST again after 4 months (age: mean = 37.9, SD = 10.1, range = 21-66; Sex: 41 females, 57 males, 5 other/not-identified/lost). Study 1.2 was conducted to replicate Study 1.1 on a larger, age-restricted (18-35 years old), gender-balanced sample; sample size of 376 was set to detect a correlation of .2 with 95% power at a 5% significance level (i.e., a target sample size of 319) after excluding about 15% of participants who do not pass the pre-registered problem-solving accuracy criteria. Out of 377 participants who completed Study 1.2, we report the results from 332 participants (age: mean = 28.7, SD = 4.2, range =19-57; Sex: 163 females, 165 males, 4 other/not-identified).

Questionnaires

To measure math anxiety, we administered the short Mathematics Anxiety Rating Scale (sMARS). Participants responded to questions about how anxious they would feel in different math-related situations (e.g., "signing up for a math course", "studying for a math test") on a 5-point Likert scale (1 = *not at all*, 2 = *a little*, 3 = *a fair amount*, 4 = *much*, 5 = *very much*). All analyses were conducted on the average of the 25 items for each participant. (Cronbach's αs = .97 for both Studies 1.1 and 1.2). To isolate math-specific component of math anxiety, we also used an adaptation of the sMARS designed to measure anxiety about reading (e.g., "signing up for an English course" and "studying for an English test"), dubbed the short Reading Anxiety Rating Scale (sRARS; αs = .97 for both studies).

To control for other forms of anxiety, we also measured participant's trait anxiety, test anxiety, and social desirability. Trait anxiety was assessed using the trait component of the State-Trait Anxiety Inventory (Spielberger, 1983) in which participants rated how frequently they experienced feelings of anxiety and calmness (e.g., "I feel nervous and restless" and "I make decisions easily"). Test anxiety was assessed using the Test Anxiety Inventory (Spielberger, 1980) in which participants rated how anxious they feel in 20 test-related situations (e.g., "during tests I feel very tense" and "I feel confident and relaxed while taking tests"). In both measures, items were scored on a 1-4 scale and reverse coded where appropriate. Scores were summed for a composite measure of 20-80 (trait anxiety: αs = .96 for both Studies 1.1 and 1.2; test anxiety: αs = .96), with a higher value indicating higher level of trait or test anxiety. Social desirability was measured using the Marlowe-Crowne social desirability scale (Crowne & Marlow, 1960; α = .89 for Study 1.1 and α = .88 for Study 1.2) to check the underreporting of anxiety (Weinberger et al., 1979)

We also administered the single-item math/reading anxiety scale (Núñez-Peña et al., 2014) and the self-math/reading overlap (Necka et al., 2015), the results of which are not reported here. Summary statistics and correlation matrix of self-report and behavioral measures are reported in Tables S1-2.

The Choose-And-Solve Task

In the CAST, participants were asked to make a series of binary choices on their willingness to put effort into solving a math or word problem for varying monetary reward. Each CAST trial comprised a "choose", "solve", and "feedback" phase.

Choose Phase. Participants first entered the choose phase and were shown a screen containing two choice cards on the left and right sides of the screen (e.g., Fig. 1A); "easy" choice cards always offered 2 cents and “hard” choice cards offered one of five possible reward amounts (2, 3, 4, 5, and 6 cents). The domain (i.e., math or word) of the choice cards was kept the same within a trial. Participants were given 3 seconds to select a card by pressing one of two designated keys (the “i” key for the choice card seen on the left side of the screen and the “p” key for the choice card seen on the right side of the screen). If they did not make a selection within 3 seconds, they were automatically directed to an easy problem with 1 cent. The critical dependent measures in the CAST were *the hard math and word choice probabilities* (math and word HCPs; i.e., probability of choosing the hard choice cards that offer more than 3 cents) because choosing the hard choice cards that offer more than 3 cents was always in the participants’ best financial interest (see Fig. 1C).

Solve and Feedback Phases. Participants then entered the solve phase, in which they were given 7 seconds to solve a 3-alternative problem (e.g., Fig. 1B) based on their selection of the choice card in the choose phase (i.e., easy or hard). The problem was drawn from a large pool of problems that were sorted by seven difficulty levels through a prior validation study (see Supplementary Materials for details). When participants chose the easy card, problems in the easiest level were given. The difficulty of hard problems was continuously calibrated to a target accuracy of 70% regardless of participants’ competence using a 2-up-1-down staircase method; the difficulty level increased after two successive correct trials, with the maximum level of 7 (the hardest level), and decreased after one incorrect trial, with the minimum level of 2 (see Fig. 2A for two exemplar participants). Capitalizing on the adaptive difficulty calibration, *the math and word difficulty levels (ADLs)* were defined as the average level of the hard problems that one encountered.

In math trials, participants were presented with a multi-digit multiplication problem whose solution was missing one digit. They were provided with an answer bank of three digits and were given 7 seconds to select the missing digit from the three options. In word trials, participants were provided with common English words with one letter removed. Again, they were provided with an answer bank of three letters and were given 7 seconds to select the missing letter from the three options to complete the word. Participants made their selection by pressing one of three designated keys ("i", "o", and "p" for the left, middle, and right options, respectively). To discourage participants from making quick guesses, key responses were not registered by the paradigm until 1.5 seconds after problem onset. After participants entered their selection or the time was up, the correct answer was displayed along with the number of remaining trials, and if correct, the reward offered was added to the total reward. Participants then proceeded to the next trial at their own pace by pressing the enter or space key.

The problem-solving accuracy criteria were based on participants' performance in easy math and word problems, which were expected to yield over 90% accuracy; participants whose accuracy was below 70% in either easy math or word problems were excluded from the analysis because their perception of expected rewards was assumed to be very different to the majority of participants, whose accuracy was over 90%. We preregistered this exclusion criteria in Study 1.2.

No-Choice Trials. Calculating the math/word competence and easy problem accuracy requires participants to solve a minimum number of both hard and easy problems. However, in Study 1.1 seven participants never chose the hard choice card, and two participants never chose the easy choice card. To address this issue in Study 1.2, we introduced the no-choice trials in which only one choice card was presented during the choose phase. In these trials, participants were instructed to accept the single choice card by pressing the key corresponding to the side of the screen that the card was presented on (i.e., "i" for left and "p" for right); unlike in the choice trials, the solve phase of these no-choice trials did not begin until they pressed the corresponding key. In Study 1.2, forty no-choice trials were included (ten easy math, ten hard math, ten easy word, ten hard word); easy choice cards were always valued at 2 cents, and hard choice cards were always valued at 5 cents. These no-choice trials ensured that participants encountered a minimum number of both easy and hard problems throughout the task that could be used to calculate their math/word competence and easy problem accuracy.

Experimental Procedure

Each study was uploaded as a human intelligence task (HIT) on Amazon Mechanical Turk to be completed in one session. After providing informed consent, participants first completed a series of questionnaires in the following order: math anxiety (sMARS), reading anxiety (sRARS), reading motivation questions, math motivation questions, self-math/reading overlap, single-item math/reading anxiety, trait anxiety, test anxiety, and social desirability. Ten attention check questions were embedded throughout the questionnaires; if participants missed more than two attention checks, the study session was terminated. Demographics such as gender, age, and race were collected after participants completed questionnaires and the CAST. Participants then performed the CAST, which started with practice blocks to train them on the problem format, button keys, and time restrictions. The first two practice blocks were designed to familiarize participants with the solve phase of task: all participants solved the same 12 math problems in the first block and the same 12 word problems in the second block (with presentation order fixed in ascending difficulty). The third practice block mirrored the design of the main CAST blocks (20 trials in Studies 1.1 and 1.1R; 28 trials in Study 1.2), though no monetary reward was given for performance during practice. In the main portion of the CAST, in which the performance-based bonus was determined, participants in Study 1.1 completed two blocks that each contained 50 math choice trials and 50 word choice trials (200 trials total), participants in Study 1.1R completed five blocks that each contained ten math choice trials and ten word choice trials (100 trials total), and participants in Study 1.2 completed five blocks that each contained ten math choice trials, ten word choice trials, four no-choice math trials, and four no-choice word trials (140 trials total). The location of the choice cards (left vs. right) was counterbalanced within each block. The difficulty calibration for hard problems began in the practice CAST block and continued through the main blocks. The initial difficulty level was set at level four and was adjusted on a trial-by-trial basis according to one's performance; as a result, each participant may have encountered different problems during the practice CAST block and afterward. The CAST was implemented in jsPsych (*39*), so that it could be administered over the Internet and run on participants' web browsers. A working version of the CAST used in Study 1.2 (including the practice blocks) can be found at https://kywch.github.io/CAST_jsPsych/choose-and-solve-task.html.

Compensation for each study is as follows: each Study 1.1 session comprised the questionnaires, the practice blocks, 200 trials of the CAST *without* the no-choice trials, post-task questions, a perceptual metacognition task (Fleming et al., 2010; not reported here), and demographic questions. Participants were paid the base of $1.50 plus performance-based bonus of up to $8.00 (total: M = $7.55, SD = $0.62). Each Study 1.1R (i.e., the retest of Study 1.1) session comprised the CAST and post-task questions only: 100 trials of the CAST without the no-choice trials and 100 trials of the pilot version of modified CAST (not reported here). Participants were paid the base of $3.00 plus performance-based bonus of up to $8.80 (total: M =

$9.56, SD = $0.74) Each Study 1.2 session comprised the questionnaires, 140 trials (including 40 no-choice trials) of the CAST, post-task questions, and demographic questions. Participants were paid the base of $2.00 plus performance-based bonus of up to $5.40 (total: M = $5.46, SD = $0.58). The pdf version of Study 1.2 Qualtrics survey is available at https://osf.io/t4wju/.

Statistical Analysis

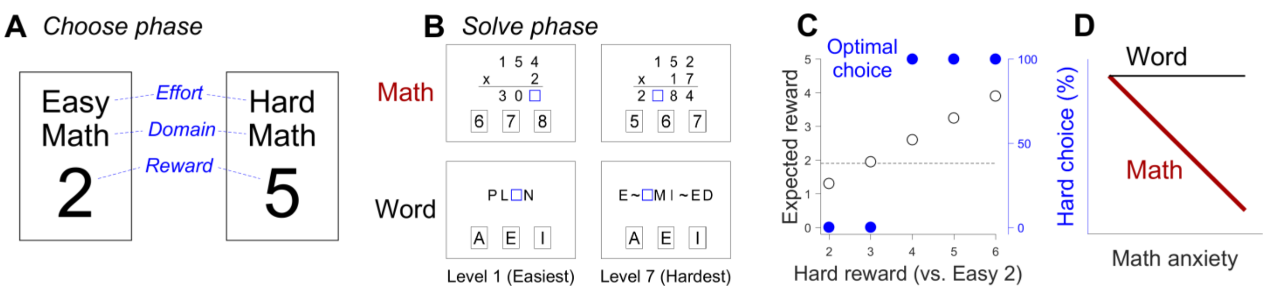
All statistical tests were performed using MATLAB R2015b. The *corrcoef* function was used to calculate the effect size (95% CI) of Pearson's correlation, the *polyfit* and *polyconf* functions were used to calculate the 95% confidence band of a regression, and the anova1 function was used to calculate F statistics. Cronbach alpha was calculated using the *CronbachAlpha* function, which can be obtained from https://www.mathworks.com/matlabcentral/fileexchange/38320. To perform the participant-level LMM analyses, the *fitlme* function in the Statistics and Machine Learning Toolbox was used, which allows incorporating random effects. The LMM results were replicated with a logistic regression (i.e., the binomial distribution was specified for the math HCP) using the *fitglm* function. The independent variables were not transformed.

Results

Behavioral Task and Hypothesis.

We collected data across a series of experiments in which participants performed our effort-based decision-making task, the choose-and-solve task (CAST; see Tables S1-2 for descriptive statistics and correlation matrix of the self-report and behavioral measures). Each CAST trial was either a math or word trial comprised of a "choose", "solve", and "feedback" phase. In the choose phase (Fig. 1A), participants were given 3 seconds to choose between two choice cards, one labeled "easy" and the other labeled "hard." "Easy" choice cards always offered a 2 cent reward for a correct response in the subsequent solve phase. “Hard” choice cards offered one of five possible reward amounts (2, 3, 4, 5, and 6 cents) so that we could obtain a psychometric curve for choosing the hard option as a function of reward and decrease habituation to repeated conditions. After making a selection in the choose phase, participants progressed to the solve phase in which they were given 7 seconds to solve the corresponding easy or hard math/word problem (Fig 1B). Participants then progressed to the feedback phase in which they received accuracy feedback on their problem-solving (i.e., correct vs incorrect) and were informed of the reward amount they earned for the problem.

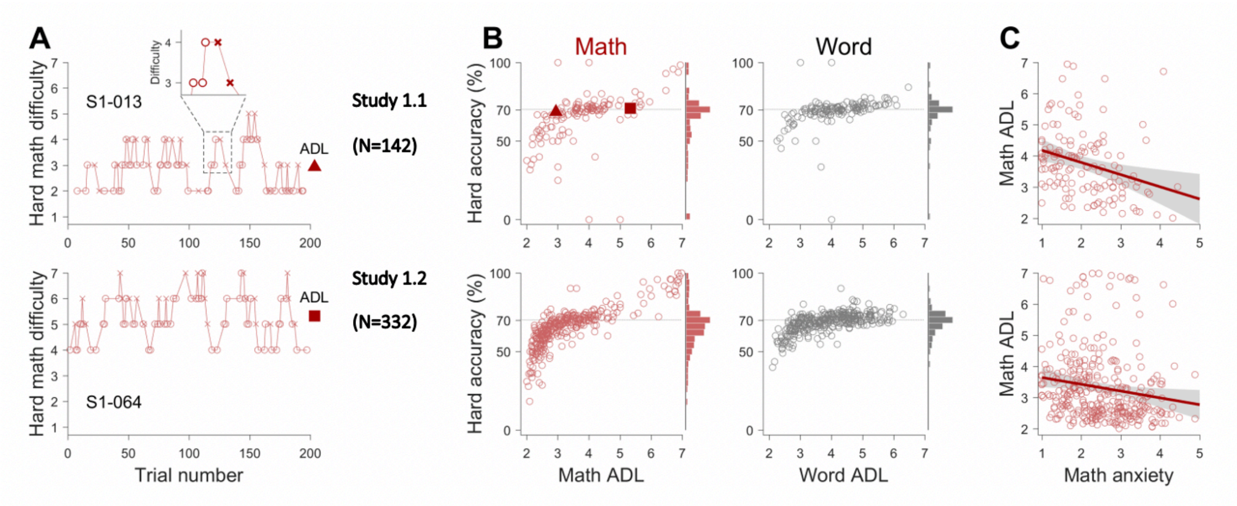
Figure 1. *Behavioral Task and Hypothesis*



Note. A) The choose phase of the choose-and-solve task (CAST). In each CAST trial, participants were asked to choose between “easy” (i.e., low-effort) choice cards, which always offered 2 cents, and “hard” (i.e., high-effort) choice cards, which offered one of five possible reward amounts (2, 3, 4, 5, and 6 cents). The domain (either math or word) of the choice cards was kept the same within a trial. (B) Four example problems in the solve phase of the CAST. Participants were asked to fill the blue square to make a correct equation (math) or an English word by selecting one of three options below. In word problems, ‘~’ is used to in place of some characters to make problems harder. The problems were sorted by seven difficulty levels through a validation study (Supplementary Materials). Word answers: PL[**A**]N, EX[**A**]MINED. Math answers: 30[**8**], 2[**5**]84. (C) Expected reward and optimal decision-making as a function of the reward offered in the hard option (the horizontal axis). The dashed horizontal line represents the expected reward (the left vertical axis) of the easy option given the expected accuracy of 95%, and the black open circles represent the expected reward of the hard options, given the expected accuracy of 70%. The blue filled circles indicate the optimal choice probability of the hard options in each reward condition to maximize monetary reward based on expected reward values. (D) Math-specific effort avoidance hypothesis. The hard choice probability (HCP; the vertical axis) was defined by averaging the individual HCPs in the 4, 5, 6 cent conditions (panel C). We predicted that math anxiety would be negatively correlated with the math HCP (the red thick line) but not with word HCP (the black line).

In the CAST, we reasoned that a rational participant who is trying to maximize earnings would make choices based on the expected values of the easy and hard choice cards (i.e., choose the option with higher expected value), where expected values are determined by the reward at stake and one's expected accuracy. However, it is possible that less competent participants might also avoid hard options if they experience poor accuracy in solving hard problems. Thus, we aimed to maintain experienced accuracy at a constant level across participants to minimize the possibility that any observed differences in the choice behavior is driven by the variability in problem-solving accuracy arising from differences in participants' competence. To do so, we sorted a set of 1,999 math problems and a set of 1,858 word problems based on their solving difficulty (Supplementary Materials) and used an adaptive staircase procedure (Fig. 2A; Materials and Methods) to ensure that the difficulty of the hard problems was continuously adjusted in our task to target an accuracy of 70% regardless of participants' competence. As a result, participant accuracy of the difficulty-adapted hard problems was around 70% (Study 1.1, math: 64.3±17.5%, M±SD, word: 68.8±9.3%; Study 1.2, math: 65.3±12.4%, word: 68.5±6.1%; Fig. 2B), and participant accuracy of the easy problems, which were all drawn from the easiest level of our sorting paradigm, was above 90% (Study 1.1, math: 95.4±6.0%, M±SD, word: 93.7±6.3%; Study 1.2, math: 93.2±6.9%, word: 92.5±7.2%).

Figure 2. *Adaptive Difficulty Manipulation and Validation.*



Note: (**A**) Time-courses of hard math difficulty level from two representative participants. The problem difficulty was determined by the 2-up-1-down staircase procedure (Materials and Methods). Each circle represents a correct trial, and each x represents an incorrect trial. The difficulty trajectory around trial 120 (indicated with a dashed rectangle) is magnified in the top panel to illustrate the 2-up-1-down staircase procedure. The filled triangle and square symbols on the right indicate the average difficulty level (ADL). (**B**) Relationships between math/word ADL and resulting accuracy in the hard problems. Each circle represents a participant, and the horizontal dotted line at 70% indicates the target accuracy. The filled triangle and square symbols indicate the representative participants in (A). The histograms of the hard accuracy are plotted on the right vertical axes. (**C**) Relationship between math anxiety and math ADL. Each circle represents a participant, the solid lines are the significant regression lines (Study 1.1 (top): Pearson's $r(134) = -.30$, 95% CI [-.45, -.14], $p < .001$; Study 1.2 (bottom): $r(330) = -.16$, 95% CI [-.27, -.06], $p = .003$), and the gray shades represent the 95% confidence bands.

Given these accuracy levels, the hard choice cards that offered more than 3 cents warranted a higher expected value that that of the easy choice cards, which always offered 2 cents (e.g., a hard choice card offering 4 cents with a 70% accuracy rate would hold the expected value of 2.8 cents since 4 x .7 = 2.8; the open black circles in Fig. 1C). Therefore, to maximize reward in the CAST one should choose the hard option when it offers more than 3 cents (the filled blue circles in Fig. 1C). Based on this rationale, we merged trials in which the hard choice card offered 4, 5, and 6 cents and indexed the proportion of these trials in which participants chose the hard option. The proportion of hard choice card selection was also highly correlated across trials that offered 4, 5, and 6 cents ($r > .9$), further justifying our decision to merge these three trial types to form one index. This index serves as our dependent variable, which is referred to as participants' hard choice probability (HCP) and represents the proportion of trials in which participants selected the hard choice card when it was advantageous to do so. We obtained both math and word HCPs from each participant as the CAST included both math and word trials.

We hypothesized that math anxiety would be negatively correlated with the math HCP (the red thick line in Fig. 1D), but would not be significantly correlated with word HCP (the black line in Fig. 1D), leading to a significant interaction between the math and word conditions. Findings in line with our hypotheses would suggest that math anxiety leads individuals to avoid effortful math even when it is incentivized with a high reward. Such findings would also suggest the relationship between math anxiety and effort avoidance is exclusive to the context of math. Taken together, these predictions create our math-specific effort avoidance hypothesis (Fig. 1D).

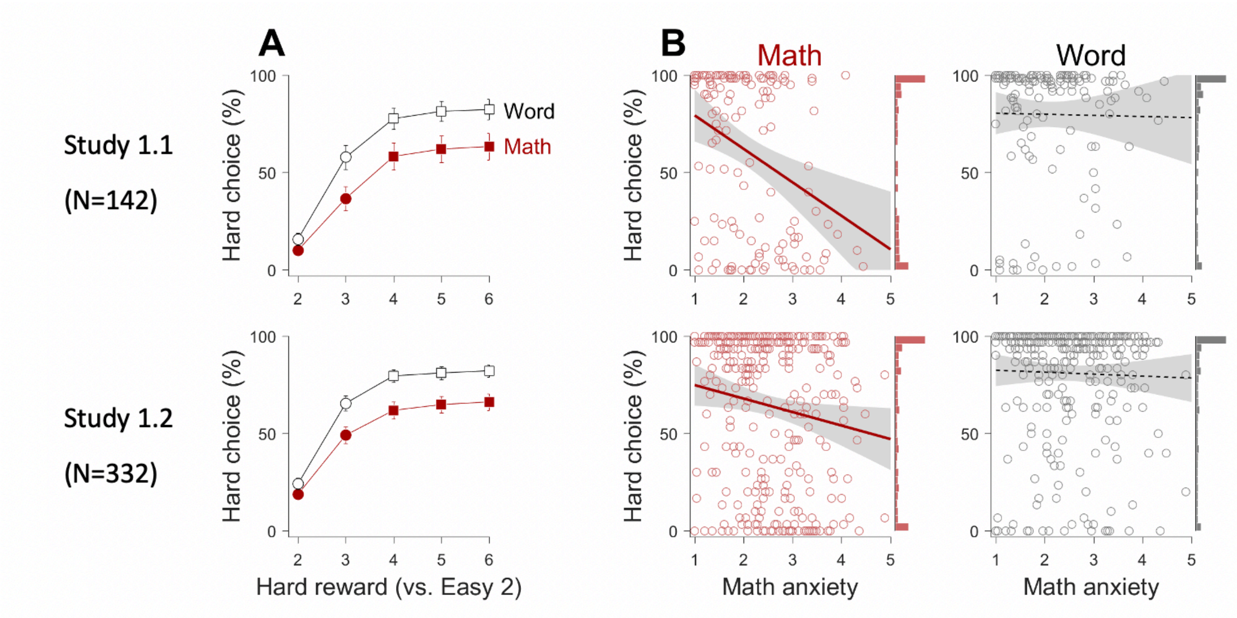
Assessing Task Validity and Reliability

Before testing our hypotheses, we assessed the validity and reliability of the CAST-derived variables. Through the adaptive difficulty manipulation (Fig. 2A), we obtained the average difficulty level (ADL) of the hard problems that each participant encountered, which might closely track their performance. Thus, we used math ADL to test the well-known negative association between math anxiety and math performance (Ashcraft & Kirk, 2001; Dowker et al., 2016; Foley et al., 2017). Consistently, we found that math anxiety was significantly negatively correlated with math ADL (Fig. 2C; Study 1.1: Pearson's $r(134) = -.30$, 95% CI [-.45, -.14], $p < .001$; Study 1.2 (preregistered): $r(330) = -.16$, 95% CI [-.27, -.06], $p = .003$), suggesting that ADL is a good proxy for one's performance. Next, we examined the temporal stability of ADL and HCP within session to assess whether the CAST led to participant fatigue. We reasoned that fatigue would lead to decreased performance and increased effort avoidance, resulting in the decrease in ADL and HCP across blocks and thus negative slopes. In contrast, however, the observed slopes of math/word ADL and HCP were significantly positive across blocks (Fig. S1; with an exception of Study 1.1 math HCP, which showed a nonsignificant positive slope), suggesting against participant fatigue. Finally, we examined the test-retest reliability of ADL and HCP between sessions that were 4-months apart (Studies 1.1 and 1.1R; Materials and Methods). We found significant positive test-retest correlations in all math/word ADL and HCP measures (Fig S2; math ADL: Pearson's $r(92) = .62$, 95% CI [.47, .73], word ADL: $r(92) = .63$, 95% CI [.49, .74], math HCP: $r(101) = .64$, 95% CI [.51, .74], word HCP $r(101) = .68$, 95% CI [.56, .78], all ps < .001). Note that many cognitive tests that are widely used clinically and for research (e.g., working memory tasks) have test-retest correlations that are in the 0.3–0.7 range (Lowe & Rabbitt, 1998; Piper et al., 2015). Together, these results show that the CAST provides reliable measures of performance and choice behavior.

Testing the Math-Specific Effort Avoidance Hypothesis.

To test the math-specific effort avoidance hypothesis, we conducted an exploratory study (Study 1.1) and examined the relationships between math anxiety and math/word HCP. We found that participants' HCP generally increased as the reward value for choosing the hard option increased in both the math and non-math conditions (Fig 3A). We also found that math anxiety was negatively correlated with math HCP (the top left panel in Fig. 3B; Pearson's $r(140) = -.34$, 95% CI [-.48, -.19], $p < .001$) but not with word HCP (the top right panel in Fig. 3B; $r(140) = -.01$, 95% CI [-.18, .15], $p = .86$).

Figure 3. *Math-Specific Effort Avoidance*



Note: (A) Observed HCP as a function of the reward offered in the hard option (the horizontal axis; the easy option always offered 2 cents). The circles and squares specify the HCP in each reward condition averaged across participants, and especially, the squares represent the conditions in which the hard choice is optimal (see Fig. 1C). Filled red symbols specify the math condition, and open black symbols the word condition. Error bars indicate standard error of the mean (SEM) across participants. (B) Relationships between math anxiety, math HCP (left), and word HCP (right). Each circle represents a participant, the solid lines are the significant regression lines (the left Math panels; Study 1.1: $r(140) = -.34$, 95% CI [-.48, -.19], $p < .001$; Study 1.2: $r(330) = -.15$, 95% CI [-.26, -.05], $p = .005$), the dashed lines are the nonsignificant regression lines (the right Word panels; Study 1.1: $r(140) = -.01$, 95% CI [-.18, .15], $p = .86$; Study 1.2: $r(330) = -.03$, 95% CI [-.14, .08], $p = .60$), and the gray shades represent the 95% confidence bands. The histograms of HCP are plotted on the right vertical axes.

To examine whether the relationship between math anxiety and effort avoidance is exclusive to the context of math, we conducted a linear mixed-effect model (LMM) analysis to test the interaction between domain (math/word) and math anxiety on HCP (Fig. 1D). We controlled for variables related to individual differences in problem-solving such as hard vs. easy accuracy and response time (RT) since they were correlated with math anxiety (Table S1) and could have confounded participants' choice behavior (see next section for more thorough explanation). In this model, the dependent variable was participants' HCP, and the fixed effects were domain, math anxiety, and their interaction. Also, participants' accuracy and RT of easy problems, accuracy and RT of hard problems, and ADL were added as fixed effects for the math and word conditions, respectively. The model (*df* = 267) explained 62.6% of the variance (adjusted R^2); the full results are presented in Table S3. We found a significant effect of math anxiety (β = -0.12, 95% CI [-0.19, -0.05], $p < .001$) and a significant interaction between domain and math anxiety on HCP (interaction β = 0.11, 95% CI [0.04, 0.18], $p = .001$), confirming that the relationship between math anxiety and math HCP significantly differed compared to that between math anxiety and word HCP.

To replicate the findings from Study 1.1, we conducted a confirmatory study with a larger, age-restricted, and gender-balanced sample (Study 1.2) after pre-registration, https://osf.io/9vpgm. Again, we found that math anxiety was negatively correlated with math HCP (the bottom left panel in Fig. 3B; $r(330) = -.15$, 95% CI [-.26, -.05], $p = .005$) but not with word HCP (the bottom right panel in Fig. 3B; $r(330) = -.03$, 95% CI [-.14, .08], $p = .60$). Since the problem-solving variables in Study 1.2, such as hard vs. easy accuracy and RT, were also correlated with math anxiety, even in the word condition (Table S2), we conducted a LMM analysis in the same manner as in Study 1.1 to test the math-specific effort avoidance while controlling for the problem-solving variables. The model (*df* = 655) explained 71.6% of the variance (adjusted R^2), and the full results are presented in Table S4. Again, we confirmed a significant effect of math anxiety (β = -0.05, 95% CI [-0.09, -0.00], $p = .03$) and a significant interaction between domain and math anxiety on HCP (interaction β = 0.06, 95% CI [0.02, 0.10], $p = .003$). These results demonstrate that individuals who experience math anxiety choose to avoid exerting greater levels of effort in math, even when it is highly rewarded, and provide a strong evidence for the math-specific effort avoidance hypothesis.

Examining Potential Problem-Solving Confounds on the Math-Specific Effort Avoidance.

Our finding of the math-specific effort avoidance may have been confounded by at least two problem-solving behaviors that are less related to math anxiety. First, participants only received rewards when they solved problems correctly, so their problem-solving accuracy may have affected their perceived value of the hard options and their choice behavior. Despite our efforts to hold the accuracy constant with a computer-adaptive paradigm, we observed a significant negative correlation between math anxiety and hard math accuracy (i.e., the higher the math anxiety, the lower the math accuracy; Tables S1-2, see Fig. S3A for Study 1.2 results). Based on this correlation, one could argue that participants with math anxiety avoided hard math because they experienced lower hard math accuracy than their less-math-anxious peers. However, we also observed a significant negative correlation between math anxiety and hard word accuracy in Study 1.2, $r(330) = -.21$, 95% CI [-.31, -.11], $p < .001$ (Fig. S3B), but did not observe word effort avoidance (Fig. 3B). Moreover, we confirmed a significant association between math anxiety and math HCP even after controlling for problem-solving variables (Tables S3-4). These results suggest that the math-specific effort avoidance cannot be explained by differences in problem-solving accuracy.

Second, participants with math anxiety may have avoided hard math problems because they did not expect to solve these problems within the 7-second time limit. We examined math anxiety in relation to the proportion of hard trials in which participants ran out of time while solving problems (Fig. S3C) and found that all participants provided responses to most of the hard math problems within the time limit (the proportion of hard math timeout: 4.4±5.4%, M±SD, range [0%, 36.4%]) and that the proportion was not significantly correlated with math anxiety in Study 1.2, $r(328) = -.05$, 95% CI [-.16, .06], $p = .39$, ruling out this possibility.

Moreover, we found that math anxiety was negatively correlated with the amount of time spent on solving hard math problems (i.e., the higher the math anxiety, the shorter the problem-solving time for hard math), $r(330) = -.18$, 95% CI [-.29, -.07], $p = .001$ (Fig. S3C). This suggests that participants with higher levels of math anxiety may have been engaging in even greater math effort avoidance by "guessing" on hard math problems, a speculation which is also supported by the significant negative correlation between math anxiety and hard math accuracy (Tables S1-2).

Linking Math-Specific Component of Math Anxiety and Math Effort Avoidance.

Previous research (Hembree, 1990; Dew et al., 1984; D'Ailly & Bergering, 1992) reported that math anxiety is correlated with other types of anxiety, such as test anxiety and trait anxiety. Similarly, we found that math anxiety was positively correlated with test anxiety, trait anxiety, and reading anxiety in our samples (Tables S1-2). Thus, it is possible that the observed association between math anxiety and math effort avoidance could be driven by the non-math-specific, general component of anxiety that is shared across math anxiety and other types of anxiety as suggested by previous research (D'Ailly & Bergering, 1992).

Therefore, we tested whether the association between math anxiety and math effort avoidance holds after controlling for other types of anxiety by conducting comprehensive LMM analyses on Study 1.1 ($df = 116$, adjusted R^2=41.6%; see Table S5 for details) and Study 1.2 ($df = 321$, adjusted R^2=47.0%; see Table 1 for details). The variables related to problem-solving, such as math ADL and accuracy/RT of easy and hard math, were added as fixed effects, as those were correlated with both math anxiety and math HCP (Tables S1-2). We confirmed a significant effect of math anxiety on math HCP (Study 1.1: $\beta = -0.19$, 95% CI [-0.30, -0.09], Study 1.2: $\beta = -0.09$, 95% CI [-0.14, -0.04], both ps < .001) after controlling for these variables, suggesting that math effort avoidance is driven by the math-specific component of math anxiety. We also ran generalized binomial regression analyses in order to address the non-normal distribution of math HCP (see the histogram of math HCP in the right vertical axes in Fig. 3B), and confirmed a significant effect of math anxiety on math HCP (Study 1.1: β = -1.22, 95% CI [-2.23, -0.20], p = .02; Study 1.2: β = -0.49, 95% CI [-0.92, -0.03], p = .03; see Tables S6-7 for the full results). Taken together, these findings establish a robust link between math anxiety and math effort avoidance.

Table 1. *Results of Comprehensive LMM Analysis for Study 1.2*

Predictor	β coefficient [95% CI]	SE(β)	t(321)	p
Intercept	-0.11 [-0.68, 0.46]	0.29	-0.38	.70
Word HCP	0.74 [0.64, 0.85]	0.05	14.04	< .001
Math anxiety	-0.09 [-0.14, -0.04]	0.02	-3.60	< .001
Reading anxiety	0.05 [-0.00, 0.09]	0.02	1.93	.05
Trait anxiety	-0.001 [-0.003, 0.001]	0.001	-0.81	.42
Test anxiety	0.003 [0.000, 0.007]	0.002	2.16	.03
Easy math accuracy	-0.03 [-0.62, 0.55]	0.30	-0.12	.91
Easy math RT	0.01 [-0.06, 0.08]	0.04	0.22	.82
Hard math accuracy	0.14 [-0.29, 0.57]	0.22	0.62	.53
Hard math RT	-0.03 [-0.08, 0.02]	0.03	-1.30	.19
Math ADL	0.08 [0.03, 0.12]	0.02	3.23	.001

Note: Dependent variable: math HCP. Independent variables were not transformed. Random effects: the random intercepts for age, gender, education level, highest level of math taken, current math-taking, ethnicity, race, and income. All 332 rows (participants) were entered into the model. The maximum likelihood estimation method was used to fit the model. df = 321. Adjusted R^2 = 47.04%. 95% confidence intervals are stated beside the βs.

Discussion

Math anxiety has long been hypothesized to be associated with math avoidance (Dutton, 1951; Richardson & Suinn, 1972; Hembree, 1990; Ashcraft, 2002; Maloney & Beilock, 2012). However, little research has directly investigated this relationship and potential underlying mechanisms, most likely due to the absence of a reliable avoidance measure. We aimed to fill this void in the literature with our novel effort-based decision-making paradigm, the "Choose-and-Solve" task (CAST; Figs. 1-2). By developing a paradigm in which one can manipulate the levels of effort and reward associated with solving math and non-math problems, we demonstrated that math anxiety is associated with math-specific effort avoidance over and above math performance (Fig. 3). Moreover, the association between math anxiety and math effort avoidance remained significant after controlling for other types of anxiety (Table 1), suggesting that the math-specific component of math anxiety drives math-specific effort avoidance. Together, these results experimentally establish a robust math anxiety-avoidance link.

Why do individuals with math anxiety avoid exerting effort in math even when it is highly rewarded? Theories of economic decision-making suggest that such avoidance may relate to individuals' subjective valuation of the effort-based costs and rewards associated with a given task (Padoa-Schioppa, 2011; Chong et al., 2016). Moreover, it is also possible that individuals with math anxiety reactively avoid math effort because they feel the need to escape, as a spider-phobic would avoid spiders, perhaps due to their highly negative, even traumatic, past experience with math (e.g., failure, humiliation, or the experience of fear). Regardless, we argue that individuals with math anxiety avoid the high-reward, high-effort math options because they perceive the costs of effortful math engagement to outweigh its benefits. Unfortunately, however, this behavioral study cannot differentiate whether math effort avoidance is due to decreased valuation of math-related rewards, greater anticipation of math effort costs, or reactive fear toward math. Moreover, the observed correlation values between math anxiety and math effort avoidance were small to modest (*rs* = -.37 and -.15; Fig. 3), suggesting that there are factors other than math anxiety that also affect math avoidance behavior.

How could math anxiety lead to less valuation of reward and/or greater anticipation of cognitive effort in math contexts? Recent research using functional magnetic resonance imaging shows that math anxiety activates the pain network in anticipation of doing math (Lyons & Beilock, 2012) and the fear network while either performing math (Young et al., 2012; Supekar et al., 2015) or simply viewing mathematical symbols for a brief period (Pizzie & Kraemer, 2017). These pain and fear-related neural activations suggest that math anxiety may lead individuals to experience a concrete, visceral sensation of pain and/or fear in math situations, the sensation which may heavily discount the reward associated with math. This speculation is supported by previous research (Talmi et al., 2009) demonstrating that pain-associated monetary reward evokes attenuated neural activation in the ventral striatum, the brain region which encodes expected reward (Preuschoff et al., 2006). Simultaneously, regulating such visceral sensation requires substantial cognitive effort (Gyurak et al., 2011) so it is highly likely that individuals with math anxiety would have to exert cognitive effort in math-related situations (Ashcraft & Kirk, 2001). Interestingly, math-anxious individuals who are able to employ greater cognitive control can overcome the adverse effects of math anxiety (Lyons & Beilock, 2012).

Among a few differences between Studies 1.1 and 1.2, it is worth noting that although the observed correlations between math anxiety and math HCP were significant in both studies, the correlation was smaller in Study 1.2 (*r* = -.15 vs. -.37 in Study 1.1; Fig 3). Why are the correlation values different? In our analysis of the data from Study 1.1, we found that a few participants completely avoided solving hard problems by always choosing easy options. Realizing that calculating math/word ADL requires participants to solve a minimum number of hard problems, we introduced no-choice trials in Study 1.2 so that participants had to solve at least 10 hard math and 10 hard word problems. It is possible that this forced exposure to hard math problems during the task reduced math effort avoidance in Study 1.2. Consistent with this notion, exposure therapy is known to be effective at reversing avoidance behavior in other forms of anxiety and phobia (Abramowitz et al., 2012). Increasing math exposure through computer games (Jansen et al., 2013) or intensive tutoring (Supekar et al., 2015) has been shown to provide positive math experience and improve math performance in students with math anxiety, thereby potentially turning the vicious cycle of math failure→ increased anxiety→ increased avoidance→ increased failure into a virtuous cycle of math success→ increased confidence→ increased approach→ increased success (Carey et al., 2016; Jansen et al., 2013).

Choosing to avoid challenging math can start a vicious cycle of math anxiety that results in limited math practice, poor math performance, increased math anxiety, and additional math avoidance (Ma & Xu, 2004; Carey et al., 2016). Students with math anxiety often choose to take fewer math-related courses and consequently pursue fewer STEM-related occupations than their less-anxious peers (Hembree, 1990; Ashcraft, 2002; Maloney & Beilock, 2012). By tackling math avoidance early, we may be able to break this vicious cycle before critical academic and occupational choices are made. We envision that our novel task, the CAST, will be used to identify young children and adolescents who have trouble putting effort into math so that targeted interventions can be introduced to reduce their math avoidance and math anxiety. Future research should therefore explore the utility of the CAST in more naturalistic settings in order to validate and optimize its effectiveness for early identification of math effort avoidance.

STUDY 2. EFFORT AVOIDANCE IN AN APPLIED CONTEXT

The results from Study 1 of this dissertation provide substantial support for our theory of math-specific effort avoidance: individuals with higher levels of math anxiety selected easier, low reward tasks over harder, high-reward tasks, but only in the math context. These findings suggest that math anxiety may lead individuals to avoid exerting effort in math-related tasks, which can have implications for performance in academic contexts. The next chapter of the current dissertation seeks to examine this idea.[1]

In Study 2, I hypothesized that math avoidance occurs within the context of a mathematics classroom, and that it manifests as the avoidance of effort within a course. I operationalized effort avoidance as the avoidance of effortful study strategies. This idea is grounded in research findings that highlight the critical role learning techniques and self-regulated use of study strategies play in student performance (Dunlosky et al., 2013; Pintrich & De Groot, 1990). Additionally, high and low-achieving students have been found to differ in how they engage with various study strategies, and these differences have been linked to differential performance outcomes (DiFrancesca et al., 2016.; Proctor et al., 2006; Yip, 2007). Given these findings, it seems plausible to predict that gaps in performance between high and low math-anxious students may be the result of differential study behaviors. If math-anxious students avoid effortful study strategies that are effective in advancing proficiency, they may lower their exam performance and exacerbate their difficulties with math.

Therefore, in the current study I examined the relation between math anxiety and math avoidance by assessing the study strategies and exam scores of students enrolled in a math

---

[1] The work reported in this chapter has been submitted for publication. The current reference is: Jenifer, J.B., Rozek, C.S., Levine, S.C., Beilock, S.L. (2020). Effort(less) Exam Preparation: Math Anxiety Predicts the Avoidance of Effortful Study Strategies. Manuscript submitted for publication.

course. I hypothesized that math anxiety would be associated with effort avoidance during exam preparation, as measured both by the quantity (i.e., study time allocation) and quality (i.e., prioritization of difficulty) of students' engagement with effortful study strategies. I also predicted that students' engagement with effortful study strategies would partially mediate the association between math anxiety and their performance on a math exam.

Materials and Methods

Participants

260 students enrolled in Advanced Placement (AP) Calculus AB at a public, Midwestern high school were invited to complete our survey. Our decision to recruit students taking AP Calculus was based on the rationalization that all enrolled students would prepare for and take the same standardized exam, which would allow us to have the same reliable outcome measure for all participants. We also reasoned that any trends of avoidance behavior found in a rigorous, elective math course such as AP Calculus would likely hold within a standard, non-optional math course.

Parents were sent a letter informing them of the study and how they could opt out of sharing their student's data with researchers. Students were similarly allowed to opt out of sharing their data with researchers. All procedures were completed in accordance with the guidelines of the University of Chicago Institutional Review Board. We report results from 190 students who completed the survey (75% response rate) and did not opt out of sharing data with researchers (six students opted out of sharing their data). Our sample was 49% female, 70% White, 13% Latino, 10% African American, 6% Asian, 1% Native American, and 1% mixed race.

Measures

Math Anxiety. Math anxiety was measured using the shortened Math Anxiety Rating Scale (sMARS; Alexander & Martray, 1989), which is a shortened version of the 98-item MARS (Richardson & Suinn, 1972). Participants responded to questions about how anxious they would feel in different math-related situations (e.g., "signing up for a math course", "studying for a math test") on a 5-point Likert scale ranging from 1 (*not at all*) to 5 (*very much*). All analyses were conducted on the average of the 25 items for each participant.

Study Strategies. Students were asked about how they planned to study for the AP Calculus AB exam using questionnaire items modeled after those used in other study strategy and avoidance behavior questionnaires (Midgley et al., 2000; Pintrich, 1991). Our questionnaire included three items that were critical to our research question on effortful study strategy use; these three items are described in greater detail below.

Rank Ordering of Study Strategies by Effort. To identify the study strategies that students viewed as requiring the most effort, we asked the following question: "When preparing for your AP exam for this class, which study strategies do you think would require the most work? Rank the following strategies from the one you think would require the most work (1) to the one you think would require the least amount of work (6)." Students then rank-ordered the following set of study strategies: reading textbook section(s) for the first time, re-reading textbook section(s), reviewing homework solutions, solving practice problems, reading examples of solved problems, and reviewing your notes.

Allocation of Study Time across Various Strategies. To measure the quantity of students' engagement with effortful study strategies, we asked them to report how they would allocate their study time across various study strategies with the following question: "When preparing for your AP exam for this class, what percentage of your study time would you spend doing the following activities: a) reading textbook sections for the first time, b) re-reading textbook section(s), c) reviewing homework solutions, d) solving practice problems, e) reading examples of solved problems, f) reviewing your notes?" Students reported their allocations using a sliding bar to indicate the percentage of study time they planned to allocate to each strategy. Students' total study time allocation was constrained to equal 100% across the six options.

Prioritization of Difficulty During Strategy Use. To measure the quality of students' engagement with effortful study strategies, we asked students to report how they would prioritize difficulty when solving practice problems with the following question: "When studying for the AP exam for this class, how much do you think you would prioritize (or spend time on) solving easier practice problems in comparison to solving harder practice problems?" Students reported their answers on a scale from 1 to 7, with 1 corresponding to prioritizing easier problems and 7 corresponding to prioritizing harder problems.

Exam Scores. All students in this study took the same standardized AP exam at the end of the school year to assess their knowledge of calculus. Scores for AP exams are given on a scale from 1 to 5, with 5 being the best possible score and scores of 3 and above typically counting as qualification for college credit (The College Board, 2019).

Procedure

Students completed the math anxiety and study strategy measures during their calculus class at school. Teachers were trained to administer the questionnaires during normal class time, two weeks before the scheduled AP Calculus AB exam date.

Results

Descriptive Statistics

Zero-order correlations between all study variables are reported in Appendix B. We highlight the significant correlations that are pertinent to our research questions throughout the remainder of this section.

Math anxiety scores ranged from 1 to 5 out of a possible score of 5 (M = 2.3, SD = 0.7). AP Calculus exam scores ranged from 1 to 5 (M = 3.0, SD = 1.3). This mean score reflects the national average for the AP Calculus AB exam score for the year that the study was conducted (M = 2.9, SD = 1.4; The College Board, 2018).

Isolating Effort: Which Study Strategy Did Students View as Most Effortful?

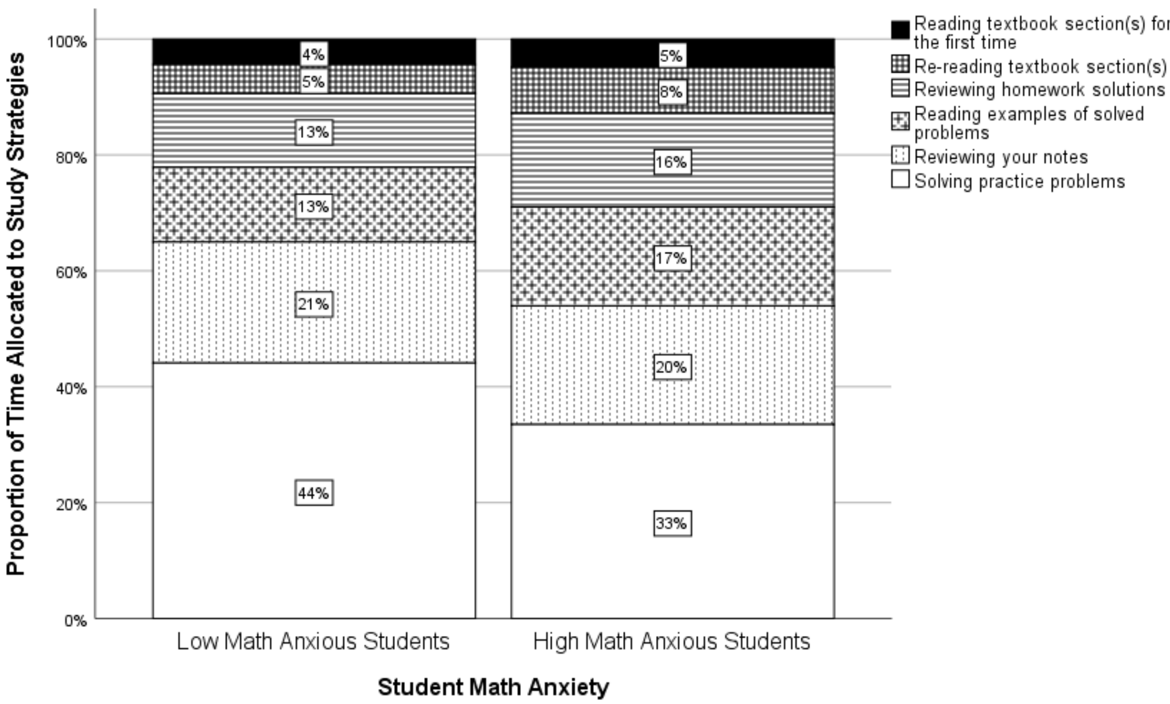
Because emerging evidence suggests that math-anxious individuals tend to avoid effortful math (Choe et al., 2019), we first assessed which study strategies students perceived as most effortful by asking them to rank a set of study strategies on the amount of effort they require (with higher ranks indicating strategies that were perceived to require more work). In ranked order from most to least work, students listed solving practice problems as most effortful (M = 1.9, SD = 1.3), followed by reading textbook section(s) for the first time (M = 2.9, SD = 1.8), re-reading textbook section(s) (M = 3.7, SD = 1.6), reviewing homework solutions (M = 4.0, SD = 1.2), reading examples of solved problems (M = 4.2, SD = 1.4), and reviewing notes (M = 4.3, SD = 1.6). Over half of students (57%) ranked solving practice problems as the most effortful study strategy. We also assessed correlations between math anxiety and individual strategy rankings to determine whether rankings differed across math anxiety (see Appendix B). Math anxiety was marginally associated with ranking solving practice problems as more effortful, $r(173) = -.15$, $p = .054$, and significantly associated with ranking re-reading the textbook as less effortful, $r(173) = .17$, $p = .027$. We note that while 190 students completed the other two questionnaire items in this study (as discussed in later sections), only 175 students completed this measure of ranking study strategy effort.

Overall, these findings identify solving practice problems as the study strategy students perceive to be the most effortful. Thus, given our original hypothesis that math anxiety would be associated with the avoidance of effortful study strategies, we can predict more specifically that math anxiety will negatively relate to the quantity and quality of students' engagement with solving practice problems during study. We explore this idea in the remaining sections.

Assessing Quantity: Does Math Anxiety Relate to Study Time Allocation across Strategies?

To measure the association between math anxiety and the quantity of students' engagement with effortful study strategies, we asked students to report how they would allocate their study time across six study strategies (see Methods). On average, students planned to spend 39% ($SD = 21.7$) of their time solving practice problems, 21% ($SD = 18.1$) of their time reviewing notes, 15% ($SD = 12.9$) of their time reviewing homework solutions, 15% ($SD = 13.2$) of their time reading examples of solved problems, 6% ($SD = 11.4$) of their time re-reading textbook section(s) and 5% ($SD = 10.7$) of their time reading textbook section(s) for the first time. Math anxiety was negatively associated with the proportion of total study time students planned to devote to solving practice problems, $r(188) = -.28$, $p < .001$, and positively associated with the proportion of their total study time students planned to spend reading the textbook for the first time, $r(185) = .21$, $p = .003$, and reviewing homework solutions, $r(188) = .15$, $p = .036$. Thus, students with greater math anxiety reported allocating less of their study time to solving practice problems and more of their study time to reading the textbook for the first time and reviewing homework solutions compared to their less-anxious peers. Figure 4 depicts how high and low math-anxious students allocated their study time, with math anxiety divided by a median split (median split was used here solely for illustrative purposes; all analyses were conducted using the full continuous measure of math anxiety). These results support our hypothesis that math-anxious students avoid engaging with effortful study strategies, specifically solving practice problems, when preparing for a math exam.

Figure 4. *Proportion of Time Low and High Math-Anxious Students Allocated to Various Study Strategies.*



Note. For illustrative purposes, math anxiety was divided into low and high levels using a median split (all analyses use the continuous measure of math anxiety).

Assessing Quality: Does Math Anxiety Relate to the Prioritization of Difficulty during Studying?

To measure the association between math anxiety and the quality of students' engagement with effortful study strategies, we asked students to report how they would prioritize difficulty when solving practice problems on a scale from 1 to 7, with 1 corresponding to prioritizing easier problems and 7 corresponding to prioritizing harder problems. Math-anxious students were significantly less likely to prioritize harder practice problems, $r(188) = -.22$, p = .002. These results support our hypothesis that math-anxious students avoid engaging with effortful study strategies by deprioritizing difficult problem-solving when studying.

Mediation

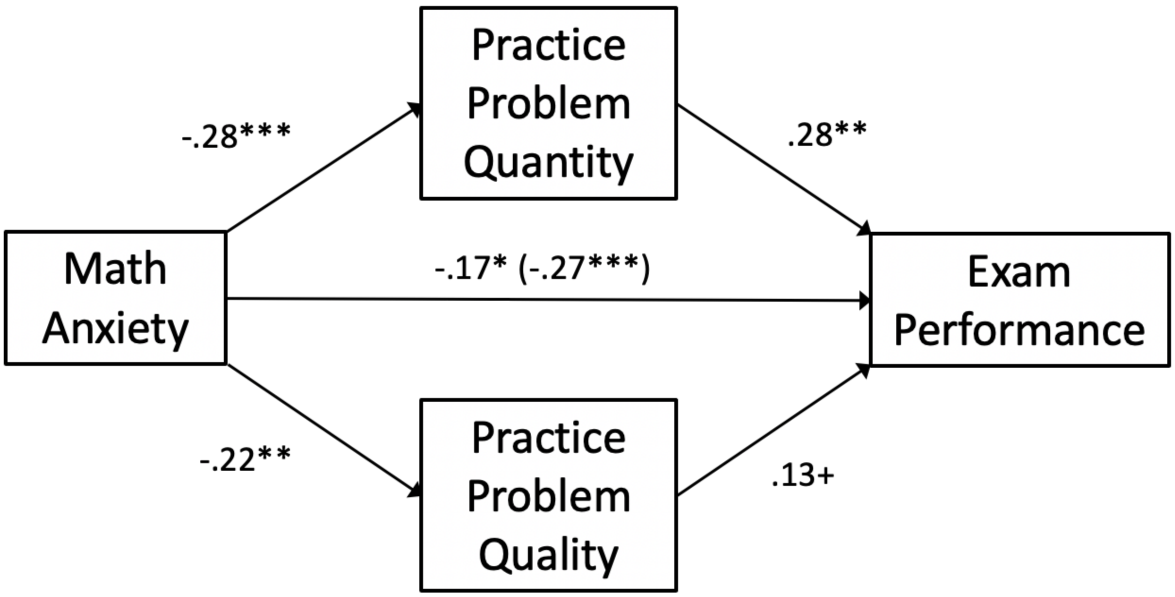
To test whether effortful study strategy engagement mediates the relation between math anxiety and math performance, we conducted both individual and multiple mediator analyses using practice problem quantity and practice problem quality as our mediator variables. We report zero-order correlations as well as the results of our multiple mediator analysis here, but note that significant indirect effects were found in the individual mediator analyses for both mediator variables (more details on the individual mediator analyses are included in the supplemental materials). Results with all standardized regression coefficients for the multiple mediator analysis are presented in Figure 5.

Math-anxious students received lower exam scores than their less-anxious peers, $r(188) = -.27$, $p < .001$. Students with higher exam scores allocated a higher proportion of their study time to solving practice problems (problem quantity), $r(188) = .35$, $p < .001$, and prioritized solving more difficult practice problems (problem quality), $r(188) = .22$, $p = .002$. Problem quantity and quality were also positively correlated with one another, $r(188) = .21$, p = .003).

We used procedures delineated by Preacher & Hayes (2008) to assess the indirect effects of math anxiety on exam performance through problem solving quantity and quality together. Standardized indirect effects were computed for each of 5,000 bootstrapped samples. The bootstrapped standardized indirect effect in this multiple mediator model was -.11, 95% CI [-.17,

-.04]. These findings are consistent with our hypothesis that both quantity and quality of effortful engagement mediate the association between math anxiety and exam performance. When examining each mediator individually within this dual mediator model, we found a significant indirect effect of math anxiety on exam performance through practice problem quantity, b = -.08, *SE* = .03, 95% CI [-.13, -.03], but not practice problem quality, β = -.03, *SE* = .02, 95% CI [-.07, .01]. Finally, there was still a significant direct effect of math anxiety on exam score with these two mediators in the model, β = -0.17, *SE* = .07, 95% CI [-.31, -.03], suggesting that avoidance of effortful engagement during studying accounted for part but not all of the association between math anxiety and exam performance. Consistent with this idea, using the coefficients from this statistical model, we can estimate that if solving math problems is just as effective for students regardless of math anxiety, the achievement gap between high and low math-anxious students could be reduced by 36% if students with greater math anxiety engaged with practice problems as much as their less-anxious peers.

Figure 5. *Mediation Model Showing Association Between Math Anxiety, Practice Problem Quantity, Practice Problem Quality, and Exam Performance*



Note. All pathways are significant at $p < .05$ except for one noted with + ($p = .07$). Pathway coefficients are standardized beta weights to allow for a consistent metric for comparisons across variables. (Individual mediation models can be found online in the Supplemental Materials). *** $p < .001$, ** $p < .01$, * $p < .05$

Discussion

Previous studies have investigated the relation between math anxiety and math avoidance by examining student course enrollment and college major selection, finding that math-anxious students avoid elective math courses and math-heavy college majors (Ashcraft & Kirk, 2001; Hembree, 1990; LeFevre et al., 1992). Here, we expand this line of research by testing whether and how the tendency to avoid math manifests for students in situations where math can't be completely avoided, such as within a mathematics course.

The results from our study show that even when math-anxious students are enrolled in a challenging math course, they still avoid effortful math by allocating smaller proportions of their study time to effortful strategies like problem solving and larger proportions to less-effortful study strategies like reading the textbook and reviewing homework solutions. Math-anxious students were also found to prioritize solving problems perceived to be easier over those perceived to be harder during exam preparation. Additionally, our mediation analysis suggests that this pattern of effortful math avoidance during exam preparation contributed to the poor exam performance of math-anxious students.

To the best of our knowledge, our research is the first to identify and characterize the avoidance behaviors of math-anxious students the real-world setting of a math course. Additionally, our study provides a new lens through which to explore the math anxiety-performance relationship: by investigating students' study behavior. Previous research suggests that students are not always the best at regulating their own use of study strategies (Chen et al., 2017; Karpicke et al., 2009). Thus, future research should explore ways to structure supports and intervene to help students manage their math anxiety during exam preparation and engage in effective study strategies that involve effortful math.

STUDY 3: INVESTIGATING THE UTILITY OF EFFORTFUL MATH ENGAGEMENT

In Study 2, I found that higher levels of math anxiety were associated with allocating a smaller proportion of study time to solving practice problems and with prioritizing easier problems over harder problems during study. These effort avoidance behaviors were subsequently found to mediate the relation between math anxiety and math performance. Based on these findings, it seems reasonable to predict that increasing math anxious students' engagement with problem-solving would improve their math performance. However, the success of such an approach depends on whether problem-solving is equally beneficial for high and low math-anxious students. The purpose of the current chapter is to test the efficacy of this approach.

One factor that might impact the utility of problem-solving as a study strategy for math-anxious students is problem-solving accuracy. Previous research finds that math-anxious individuals experience worries and ruminations that distract them during problem-solving tasks, resulting in lower problem-solving accuracy compared to their less-anxious peers (Ashcraft & Kirk, 2001). If math-anxious students experience these worries and ruminations when problem-solving during a study session, they may inaccurately solve these problems and fail to gain adequate practice with solving problems correctly. Inaccurate problem-solving, coupled with limited problem-solving in general, may therefore result in practice deficits that contribute to low math performance.

Although math anxiety may lead to inaccurate problem-solving during studying, however, these inaccuracies may not necessarily have a negative effect on math performance. While decades of research have shown the positive effects of practice testing for performance, recent research finds that even inaccurate retrieval during practice can be beneficial for learning in certain instances. For example, a study by Kornell and colleagues (2009) found that unsuccessful retrieval attempts enhanced the learning of weakly associated information compared to conditions that involved simply reading a question and answer together. Therefore, it is possible that math-anxious students can benefit from increased problem-solving engagement even if they generate inaccurate solutions.

A primary goal of the current study, then, was to investigate the role of problem-solving accuracy in the relation between math anxiety and math performance. I reasoned that if math anxiety is negatively related to problem-solving accuracy and problem-solving accuracy is positively related to test performance, then interventions suggested to increase problem-solving accuracy should help math-anxious individuals improve their test performance. Therefore, an additional goal of the current study was to investigate the utility of accuracy-related interventions for math-anxious individuals.

One potential way to improve the problem-solving accuracy of math-anxious individuals is by placing practice problems in ascending order of difficulty. This strategy could help math-anxious students practice using simple skills before moving on to more complex material, making it easier for them to solve more difficult problems. Additionally, this strategy could mitigate exposure to failure during studying, which has been shown to bolster confidence in math-anxious students and encourage them to try solving more problems (Jansen et al., 2013).

Another potentially useful way to increase math-anxious students' problem-solving accuracy is by forcing them to study via a worked-example-problem-solving (WEPS) schedule. In a WEPS schedule, learners alternate between reading a worked example of a problem and solving a problem on their own (Trafton & Reiser, 1993; Leppink et al., 2014). Students are thought to benefit from WEPS schedules because the strategy supports the development of problem-solving schemas without inducing much cognitive load, enabling all students to learn regardless of their previous knowledge or skill in the subject area. If math-anxious students are experiencing additional cognitive demands during problem-solving due to anxiety-related worries and ruminations, studying via a WEPS schedule may be particularly beneficial for them as it may ensure that they gain the knowledge and practice needed for successful test performance.

In order to explore the utility of problem-solving as a study strategy for math anxious individuals, the current experiment tested the relation between math anxiety, Practice problem accuracy and test performance through the use of a novel learning paradigm. Here, individuals learned a set of symbol relation rules and studied how to use the rules to solve symbol equations in preparation for a final test. Participants were also randomly assigned to one of four conditions that manipulated how they studied for the final test. Two specific factors related to participants' studying behavior were manipulated: a) whether practice problems were placed in ascending order or interleaved order of difficulty (Ordering Manipulation) and b) whether participants had a choice in how they engaged with each practice problem or if they were required to follow a WEPS schedule (Schedule Manipulation).

Since previous research finds a negative relation between math anxiety and problem-solving accuracy during tests, I hypothesized that math anxiety would also be negatively related to practice problem accuracy during studying (in addition to being negatively related to test performance). Additionally, given previous research on the benefits of problem ordering and WEPS schedules for Practice problem accuracy, I predicted that participants with higher levels of math anxiety would benefit from solving problems in ascending order and from studying via a WEPS schedule, resulting in greater Practice problem accuracy and greater test performance in these conditions.

Materials and Methods

Participants

Data was collected from 402 participants using Amazon's Mechanical Turk platform. Turk Panel Options were used to target an equal number of males and females whose are citizens of the United States, speak English as their first language, and are between the ages of 18 and 35. 16 people were excluded for spending less than 10 minutes or greater than 1.5 hours to complete the study. Six people who reported being outside of the 18-35-year-old age range that was specified for the study were also excluded. I also excluded 22 participants (~ six in each condition) whose predicted value in a regression relating math anxiety to test score held a cook's distance value greater than 4/n. I therefore report findings from a total of 358 participants.

Symbol Relation Learning Task

Participants completed a symbol-based learning task based on a concrete symbol system that has been used in previous research to test participant learning of symbolic math concepts (Kaminski, Sloutsky, and Heckler, 2006; De Bock et al., 2011). At the beginning of the study, participants were told that they would be learning novel symbol relations in preparation for a test that would occur at the end of the study. Participants were also told that their accuracy on the final test would determine their eligibility for a monetary bonus of $2.00. Participants then completed the learning phase of the task where they were introduced to the generic symbol system that consists of six symbol relation rules (Figure 6A). Participants then moved into the study phase of the task where they prepared for the final test by applying the learned symbol relation rules to symbol equations. The study phase consisted of 20 trials for all participants regardless of condition, and on each trial participants either read a worked example of a symbol equation problem or solve a symbol equation problem on their own (Figure 6B & C).

Participants received feedback about accuracy on all problem-solving trials. Conditional differences for the study phase are outlined below:

Choice-Interleaved Condition. Participants were given the choice to either complete a worked example or a practice problem on each of the 20 study trials (10 easy trials, 10 hard trials). Trials were presented in alternating order of difficulty, with the first trial being an easy trial.

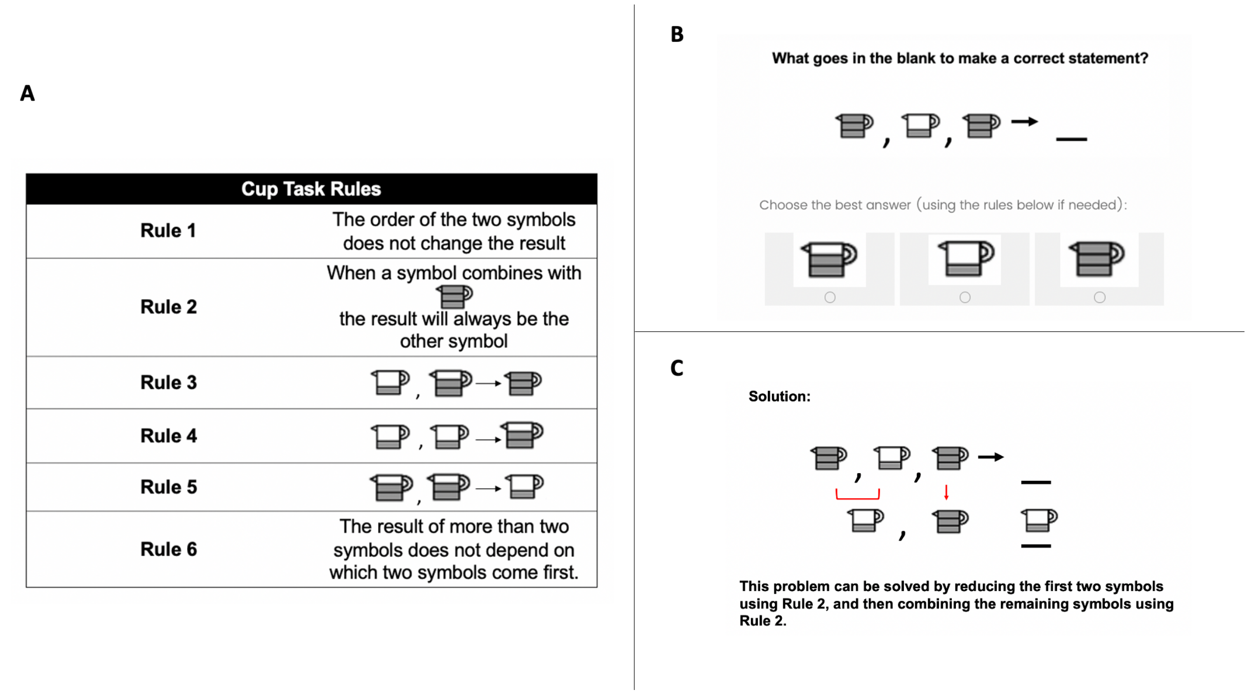
Choice-Ordered Condition. Participants were given the choice to either complete a worked example or practice problem on each of the 20 trials, with trial difficulty occurring in ascending order (i.e., 10 easy trials followed by 10 hard trials).

WEPS-Interleaved Condition. Participants were required to alternate between completing a worked example and solving a practice problem across the 20 trials. Trials were grouped into sets (i.e., one worked example trial and one problem solving trial) and sets alternated in difficulty, with the first set being an easy set.

WEPS-Ordered Condition. Participants were required to alternate between completing a worked example and solving a practice problem across the 20 trials, with trials being grouped into sets and sets occurring in ascending order (i.e., 5 easy WEPS sets followed by 5 hard WEPS sets).

After participants completed the 20 trials in the study phase, they moved on to the test phase of the task where they attempted to solve 24 symbol equation problems. Participants who solve at least 18/24 of the problems correctly received the monetary bonus of $2.00.

Figure 6. *Symbol Relation Learning Task*



Note. Only participants who selected "solve the problem" were given the option to choose an answer (Panel B). Only participants who selected to “see a worked example” were shown the solution (Panel C).

Survey Measures

Math Anxiety. To measure math anxiety, I administered the short Mathematics Anxiety Rating Scale (sMARS). Participants responded to questions about how anxious they would feel in different math-related situations (e.g., “signing up for a math course”, “studying for a math test”) on a 5-point Likert scale (1 = *not at all*, 2 = *a little*, 3 = *a fair amount*, 4 = *much*, 5 = *very much*). All analyses were conducted on the average of the 25 items for each participant.

Trait Anxiety & Test Anxiety. Trait anxiety was assessed using the trait component of the State-Trait Anxiety Inventory in which participants rated how frequently they experienced feelings of anxiety and calmness (e.g., “I feel nervous and restless” and “I make decisions easily”). Test anxiety was assessed using the Test Anxiety Inventory in which participants rated how anxious they feel in 20 test-related situations (e.g., “during tests I feel very tense” and “I feel confident and relaxed while taking tests"). In both measures, items were scored on a 1-4 scale and reverse coded where appropriate. Scores were summed for a composite measure of 20-80 with a higher value indicating higher level of trait or test anxiety.

Math Ability. Participants' math ability was measured using an 8-item numeracy scale (Weller et al., 2016). This scale is a composite of the most effective items from other existing numeracy scales.

Results

Descriptive Statistics

Table 2 reports the mean statistics for the variables of interest across each condition. A correlation matrix of all zero-order correlations can be found in Appendix C.

Math anxiety scores for the full sample ranged from 1 to 4.92 out of a possible score of 5 (M = 2.98 SD = 1.01). [1] The average test anxiety score was 47.86 (SD = 15.53) out of a possible score of 80, and the average trait anxiety score was 45.22 (SD = 11.62) out of a possible score of 80. The average math ability score was 3.96 (SD = 2.39) out of a possible score of 8.

In the Choice conditions, participants chose to solve the practice problem (rather than see a worked example) on around 85% of the easy trials and 76% of the hard trials. Participants in the WEPS conditions were required to solve the practice problem on 50% of the easy and hard trials. Practice problem choice for easy and hard trials was not significantly correlated with math anxiety (Appendix C).

---

[1] Mean and median sMARS scores in this study were higher than what has been traditionally been found in the literature (the median sMARS score here was 3.12). Additionally, while the sMARS distribution is typically right-skewed, it was normally distributed for this sample.

Table 2. *Descriptive Statistics*

	Choice-Interleaved N = 93	Choice-Ordered N = 90	WEPS-Interleaved N = 89	WEPS-Ordered N = 86
1. *Math anxiety*	3.01 (1.06)	2.92 (1.02)	2.94 (1.01)	3.03 (0.97)
2. *Test anxiety*	47.22 (16.17)	48.72 (14.97)	47.48 (15.25)	48.05 (15.90)
3. *Trait anxiety*	45.53 (11.79)	46.03 (12.13)	44.07 (12.03)	45.21 (10.51)
4. *Math ability*	3.53 (2.23)	4.21 (2.55)	4.34 (2.22)	3.76 (2.50)
5. *Easy practice problem choice (%)*	0.82 (0.29)	0.88 (0.25)	N/A	N/A
6. *Hard practice problem choice (%)*	0.74 (0.34)	0.78 (0.32)	N/A	N/A
7. *Easy practice problem accuracy (%)*	0.64 (0.32)	0.69 (0.33)	0.75 (0.30)	0.75 (0.30)
8. *Hard practice problem accuracy (%)*	0.56 (0.32)	0.61 (0.31)	0.65 (0.32)	0.66 (0.28)
9. *Test performance (%)*	0.53 (0.18)	0.53 (0.20)	0.56 (0.20)	0.55 (0.18

Note: This table reports unadjusted means. N/As for choice data are reported in WEPS conditions because participants in WEPS conditions were not permitted to choose how to study.

Results Collapsed Across Conditions

I first report the relations between math anxiety, practice problem accuracy, and test performance collapsed across all four conditions. Linear regressions were conducted controlling for test anxiety, trait anxiety, math ability. Practice problem choice (i.e., the proportion of easy and hard trials participants spent solving practice problems) was also controlled for in all regressions that included practice problem accuracy as a predictor or outcome variable.

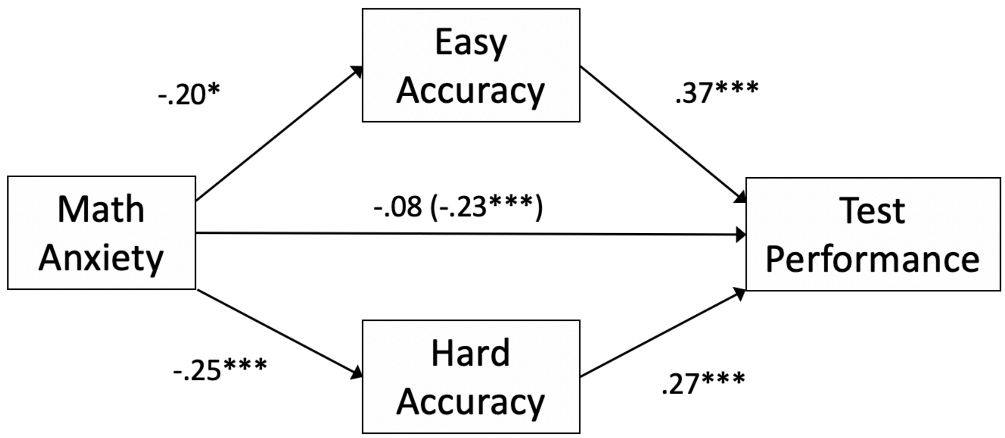
Test Performance. Math anxiety was negatively related to test performance, t(353) = -3.64, p < .001. Practice problem accuracy for both easy and hard practice problems was positively related to test performance, easy: t(343) = 13.307, p < .001, hard: t(341) = 11.19, p < .001).

Practice problem accuracy. Math anxiety was negatively related to practice problem accuracy for easy and hard problems, easy: t(344) = -.2493, p = .013, hard: t(344) = -3.26, p = .001.

Mediation. Since math anxiety was negatively related to test performance and practice problem accuracy was positively related to test performance, I also tested whether practice problem accuracy mediates the relation between math anxiety and test performance. I used procedures delineated by Preacher & Hayes (2008) to assess the indirect effects of math anxiety on test performance through easy and hard practice problem accuracy. Test anxiety, trait anxiety, math ability, and practice problem choice were included as covariates in the mediation model. Standardized indirect effects were computed for each of 5,000 bootstrapped samples. I report the results of a multiple mediation model here (including both easy and hard accuracy together in the model), but provide statistics for the individual mediations in Appendix C. Results with all standardized regression coefficients for the multiple mediator analysis are presented in Figure 7.

In the multiple mediator model, the total bootstrapped standardized indirect effect for the was -.14, SE = .04, 95% CI [-.22, -.06]. The total standardized effect of math anxiety on test performance was -.23, SE = .01, p = .001, and the standardized direct effect of math anxiety on test performance was -.08, SE = .01, p = .11. The bootstrapped indirect effect of easy accuracy in this multiple mediation model was -.08, SE = .03, 95% CI [-.14, -.01), and the bootstrapped indirect effect of hard accuracy was -.07, SE = .02, 95% CI [-.14, -.01]. Together, these findings suggest that easy and hard practice problem accuracy completely mediate the relation between math anxiety and test performance for participants in our sample. These findings suggest that intervening on practice problem accuracy may help improve the test performance of individuals who experience math anxiety.

Figure 7. *Multiple Mediation Model*



Note: Standardized beta weights presented here.

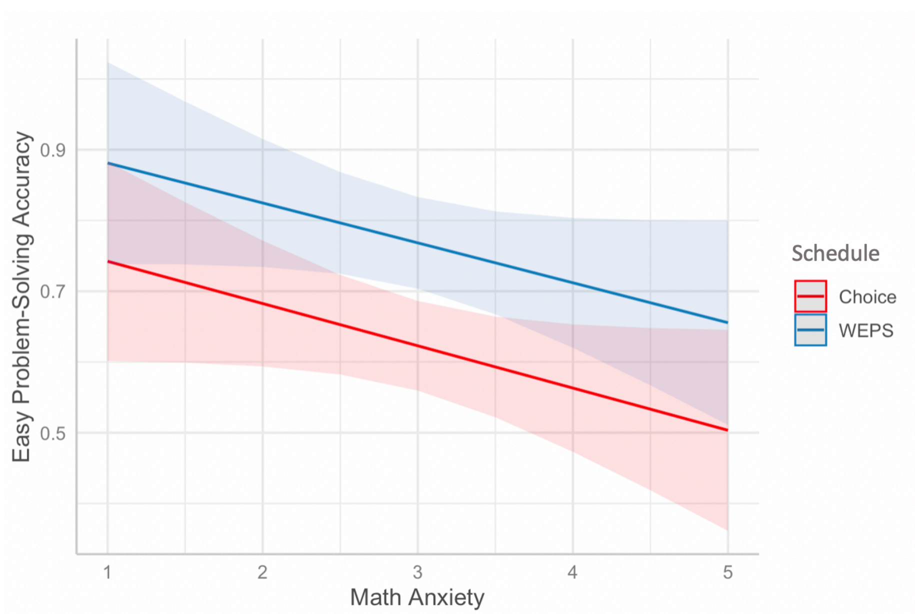
Condition Effects on Practice Problem Accuracy & Test Performance.

Since practice problem accuracy was found to mediate the relation between math anxiety and test performance, we can now test whether our condition manipulations impacted practice problem accuracy and test performance for individuals with higher levels of math anxiety. For this, I conducted a series of linear regressions that included math anxiety, ordering manipulation and schedule manipulation as predictor variables. Main effects and all two and three-way interactions of our predictor variables were tested for. Test anxiety, trait anxiety and math ability were again included as covariates. practice problem choice was also included as a covariate for in all regressions that included practice problem accuracy as a predictor or outcome variable.

Practice Problem Accuracy. We found a main effect of math anxiety on **easy** practice problem accuracy controlling for covariates; with math anxiety negatively predicting accuracy, $t(341) = -2.565$, $p = .01$). We also found a main effect of schedule, with participants in the WEPS conditions having significantly higher accuracy than those in the choice conditions, t(341) = 3.48, p = .001. All two- and three-way interactions were insignificant (Figure 8).

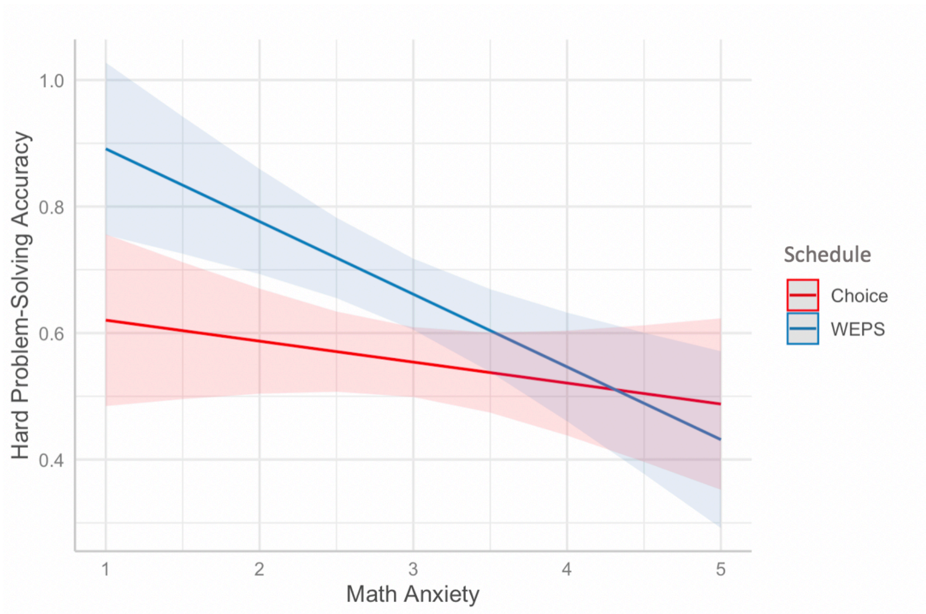
Additionally, we found a main effect of math anxiety on **hard** practice problem accuracy controlling for covariates, with math anxiety negatively predicting accuracy for hard practice problems, t(-3.29, p = .001). We also found a main effect of schedule, with participants in the WEPS conditions having a significantly higher hard practice problem accuracy than those in the choice condition, t(3.91, p < .001. The interaction between math anxiety and schedule was also significant, t = -2.25, p = .03. Based on the graph of the interaction, it appears as though the negative relation between math anxiety and hard practice problem accuracy was significantly stronger in the WEPS conditions, with the WEPS schedule primarily benefiting individuals with lower levels of math anxiety.

Figure 8. *Main Effects of Math Anxiety and Schedule on Easy Practice Problem Accuracy*



Note. The interaction between math anxiety and schedule was insignificant.

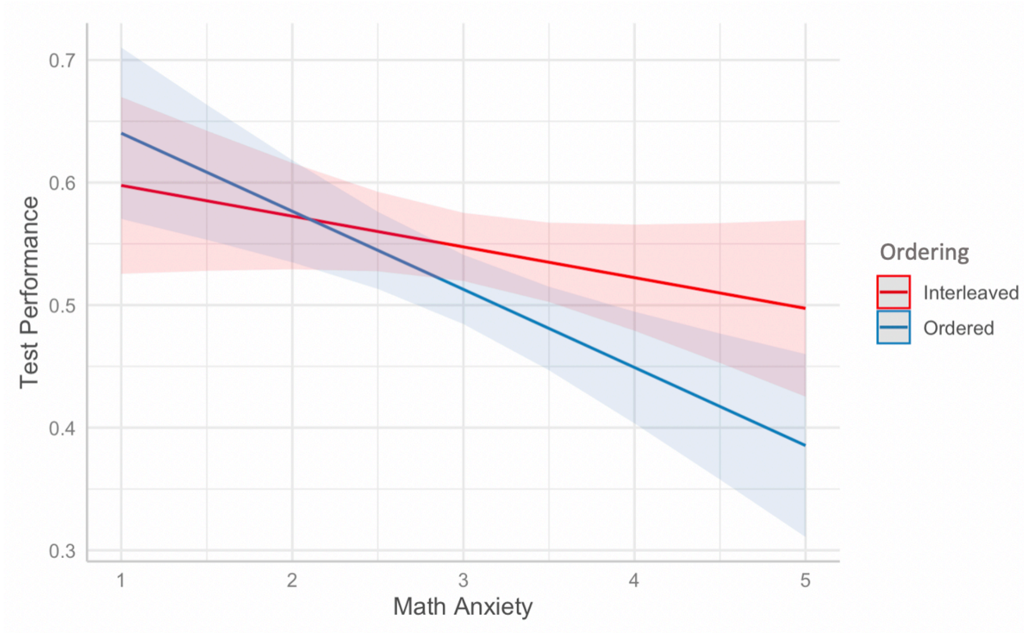
Figure 9. *Main Effects and Interaction of Math Anxiety and Schedule on Hard Practice Problem Accuracy*



Note. The interaction between math anxiety and schedule was significant.

Test Performance. We found a main effect of math anxiety on test performance after controlling for covariates, with math anxiety negatively predicting test performance $t(351) = -3.71$, $p < .001$. We also found a significant interaction between math anxiety and ordering, $t(347) = -1.98$, $p = .048$. Based on the graph of the interaction, it appears as though the relation between math anxiety and test performance was significantly weaker for participants in the interleaved conditions (Figure 10). When graphing this interaction separately for each schedule (Appendix C), this order effect appears to be most prominent in the choice conditions compared to the WEPS conditions (though we note that the three-way interaction between math anxiety, schedule, and order was insignificant).

Figure 10. *Relation Between Math Anxiety & Test Performance by Ordering*



Discussion

The primary aim of the current study was to explore the utility of problem-solving as a study strategy for math-anxious individuals. I found that math anxiety was negatively related to practice problem accuracy during studying, and that practice problem accuracy was positively related to test performance. Additionally, I found that practice problem accuracy for easy and hard practice problems completely mediated the relation between math anxiety and test performance for participants in this study. These findings suggest that the benefits of studying via practice problems may differ for high vs. low math-anxious individuals, with poor practice problem accuracy diminishing the utility of problem-solving as a study strategy for individuals with higher levels of math anxiety.

In relation to the previous findings from this dissertation, these results suggest that math anxious individuals' avoidance of effortful study strategies may be more rational than originally theorized. For example, if math-anxious learners are aware of their poor accuracy with effortful problem-solving, they may decide to engage in other, less effortful strategies that are beneficial to their learning, making their effort avoidance behaviors both strategic as well as optimal in particular circumstances. However, the finding that practice problem accuracy mediates the anxiety-performance relation also suggests that interventions targeting practice problem accuracy may be effective at improving the test performance of math anxious individuals.

Relatedly, the current study also aimed to explore whether manipulating aspects of math anxious individuals' study behavior could have a positive impact on their practice problem accuracy and test performance. Here, I found participants who studied via a WEPS schedule had significantly greater accuracy when solving easy practice problems compared to participants who were allowed to choose how to study. Surprisingly, this effect held for all participants across all levels of math anxiety, suggesting that studying via a WEPS schedule may be particularly useful for boosting the easy practice problem accuracy of both math anxious and non-math-anxious individuals.

Additionally, studying via a WEPS schedule was also found to significantly improve participants' practice problem accuracy for hard problems, though this effect seemed to only apply to individuals with lower levels of math anxiety. It's possible that individuals with higher levels of math anxiety failed to benefit from the WEPS schedule when solving hard problems because the difficulty of the problem-solving led them to experience anxiety-induced worries and ruminations that could not be diminished by the WEPS schedule. However, this finding may also be explained by differences in math ability across math anxiety levels. The math ability measure used in this study was positively correlated with practice problem accuracy and test performance but was negatively correlated with math anxiety (see correlation table in Appendix C). Thus, it may be that individuals with higher levels of math anxiety struggled to accurately solve the hard practice problems due to deficits in math ability, and that studying via a WEPS schedule was not enough to overcome these deficits. If this explanation is true, then studying via a WEPS schedule may still work to improve the hard practice problem accuracy of math anxious individuals who have higher levels of math ability. Future research should therefore explore math ability as a potential moderator of this effect.

Despite the positive effects found for WEPS schedules on easy and hard practice problem accuracy, however, a main effect of schedule was not found for test performance. One potential explanation for this finding is that the continued use of the WEPS schedule throughout the study session may have hampered student learning by limiting the number of practice problems they could solve. Due to the design of the study, learners in the WEPS conditions were limited to solving five easy and five hard practice problems, placing a cap on the number of problems they could practice solving prior to the test. Previous literature on WEPS schedules finds that engagement with worked examples within a WEPS schedule can become redundant after learners have gained proficiency, and that problem-solving is better as a technique once proficiency has been gained (Foster et al., 2018). One interesting solution to this problem that has been utilized within the literature is the use of faded worked examples, in which learners transition from fully worked examples to partially worked examples that leave steps for the learner to solve (Atkinson et al., 2000; Renkl et al., 2002). This technique may be particularly useful for improving the effect of WEPS schedules on test performance, as it both regulates study behavior to increase accuracy while also providing space for more problem-solving behavior. Future research should therefore investigate whether the use of such faded examples can optimize learning and practice problem accuracy for highly math anxious students to improve their test performance.

Although schedule was not found to have an effect on test performance, we did find a significant interaction between math anxiety and our ordering manipulation on test performance. Interestingly, this interaction was in the opposite direction of our predictions and seems to suggest that math anxious individuals benefit from studying problems when placed in interleaved order and not when they are placed in ascending order. It may be that practicing problems in interleaved order leads individuals to experience interleaved "successes" on easy problems that then motivate them on the hard problems that follow. When problems are places in ascending order, individuals may lose motivation within a block of hard problems if they are consistently experiencing poor accuracy, which could also limit learning. Surprisingly, a graph of this interaction split by schedule also suggests that interleaving may be most beneficial for math anxious individuals when they are allowed to choose how to study (and not when they are in a WEPS schedule). Although this difference in schedule was not significant, it may be an interesting direction to follow up on in future research.

Given the context of the current dissertation, an additional finding worth mentioning from this study is the absence of effort avoidance in the choice conditions. Unlike in our previous study, where math anxiety was negatively associated with problem-solving behavior, both high and low math anxious students chose to solve the practice problems in this study (i.e., the correlation between math anxiety and practice problem choice was insignificant, Appendix C). One potential explanation for this finding is that the current study employed a forced-choice study strategy design, restricting the studying options to worked examples or problem-solving. It may be that students opted to study via problem-solving because they didn't think reading worked examples would be enough to prepare them for the final test. In real-life studying scenarios, students have many alternatives to solving problems, such as reading their textbook, reading notes, etc. Students in real testing scenarios are also likely to be more familiar with the material covered by those alternative strategies given their connection to their actual courses, possibly making the strategies more comforting and desirable when feeling anxious about an upcoming exam. Future research should continue to investigate the impact alternative study strategies can play in students' study behavior.

The current study has some limitations. One such limitation is our use of an immediate post-test (rather than a delayed post-test) for evaluating learners' knowledge after studying. Previous research finds that retrieval strategies such as practice testing are often absent on immediate post-tests but emerge during delayed testing (Roediger & Karpicke, 2006). It's possible that the effects of studying via a WEPS schedule would emerge for math anxious individuals if testing was delayed, making this an interesting next step for future research.

An additional limitation of the current study is our use of a novel studying paradigm with a relatively unique problem set to measure math learning and performance. Although the symbolic problem set used in this study has successfully used in other research exploring math learning (Kaminski et al., 2008; De Bock et al., 2011), none have used it to measure studying behavior or individual differences in math learning. It's possible that the novelty of this problem set impacted participants learning and study behavior in ways that differ from how a more familiar math task would. This may explain why studying via a WEPS schedule was beneficial for the problem-solving accuracy for high and low math anxious participants: WEPS schedules are generally suggested to benefit novice learners, and in this particular task, everyone was a novice learner. This also suggests that the positive relation between WEPS schedules and problem-solving accuracy for math anxious individuals may have little to do with reducing their worries and ruminations during problem solving, and instead may be more related to increasing their knowledge and familiarity with the task. It may therefore be useful for future research to try to replicate the findings of our study with a more traditional math task to see if the accuracy-related findings hold. Such a replication would be important for understanding the generalizability of our results.

Overall, the results of this study provide preliminary evidence in support of the idea that practice problem accuracy plays a role in the relation between math anxiety and math performance and provides insight on potential ways to intervene. Future studies should therefore continue to investigate the relationship between math anxiety, effort avoidance and accuracy to gain a better understanding of how to best support the learning and performance of math-anxious students.

GENERAL DISCUSSION

General Summary

The purpose of the current dissertation was to investigate whether and how math anxiety might lead to math avoidance behaviors for individuals within a math context. Using research on global and local math avoidance behaviors as well as expectancy-value-cost models of achievement motivation, I proposed and tested a theory of math-specific effort avoidance which posits that math avoidance emerges for math-anxious individuals when they perceive the costs of effortful math engagement to outweigh its benefits.

In Study 1, I evaluated this theory of math-specific effort avoidance by analyzing the choice behavior of math-anxious individuals using a novel effort-based decision-making task. Math-anxious individuals were found to select easier, low-reward options over harder, high-reward options when selecting math (but not spelling) problems to solve, providing support for the math-specific effort avoidance theory. In Study 2, I explored the real-world consequences of math-specific effort avoidance by investigating whether math anxiety relates to students' use of effortful study strategies when preparing for a mathematics exam. Here, math anxiety was associated with the avoidance of effortful problem-solving, which partially mediated the association between math anxiety and exam performance. Finally, in Study 3 I investigated whether the utility of studying via effortful problem-solving depends on practice problem accuracy for math-anxious individuals. Practice problem accuracy was found to be a significant mediator of the negative relation between math anxiety and math performance, suggesting that intervening on accuracy during studying can help improve the math performance of math-anxious students.

The totality of this work builds upon previous research exploring the negative consequences of math anxiety, which has long been hypothesized to be associated with the avoidance of math-related activities. Together, the findings from this dissertation introduce a new theoretical contribution to the literature and highlight considerations for improving the math performance of math-anxious individuals. Additionally, each component of the current dissertation provides its own unique contribution to the math anxiety literature. The first chapter of this work provides what appears to be the first extensive review of the literature regarding math anxiety and math avoidance. Study 1 provides what is believed to be the first experimental test of the long-hypothesized relation between math anxiety and math avoidance decision-making. Additionally, Study 1 contributes a novel effort-based decision-making task to the literature that can be used to measure math avoidance in future studies. Study 2 provides an additional contribution to the math anxiety literature by testing the long-theorized mediation of the math anxiety-math performance relationship by math avoidance. This study is believed to be the first to test this important mediation relationship. Finally, Chapter 3 provides insight on how to effectively intervene on math avoidance behaviors to improve the study strategy behavior and future exam performance of highly-math-anxious individuals.

Future Directions

The findings of the present dissertation provide a strong theoretical and experimental foundation for future work. One important topic to consider in future studies is possible moderation of the relation between math anxiety and effort avoidance. Characteristics such as participant gender, SES, culture, math motivation, and math ability level have all been suggested to moderate the relation between math anxiety and math performance in previous research (Barroso, 2020; Richland et al., 2020; Wang et al., 2015). These characteristics may therefore also moderate the effect that math anxiety has on avoidance behaviors, which can have consequential effects on math performance.

Additionally, future research should continue to explore the circumstances under which effort avoidance emerges for math-anxious individuals. The absence of effort avoidance behaviors in Study 3 highlights the importance of understanding an individual's subjective valuation of all choice options available in order to make informed predictions about whether effort avoidance will occur. In the context of exam preparation, students' value of different strategies may vary depending on the course structure and utilization of each strategy.

Finally, future work should consider exploring how math anxiety relates to metacognition in order to inform students' decision-making behavior. Morsanyi and colleagues (2019) have previously outlined numerous ways in which math anxiety may impact student monitoring and control processes during studying that can have implications for later performance, many of which overlap with our findings from Study 3. Additionally, Ackerman and Thompson have recently proposed a metacognitive framework that explores the role of effort regulation in student reasoning and problem-solving (Ackerman and Thompson, 2017). Metacognitive frameworks may therefore provide crucial insight into effort avoidance behaviors for math anxious individuals and how to intervene.

Conclusion

The primary aim of the current dissertation was to investigate whether math anxiety results in math avoidance behaviors in contexts where math cannot be completely avoided. The results of the current work support the theorization that math avoidance behaviors emerge for individuals within a math context when the costs of effortful math engagement are perceived to outweigh the benefits, and that this perception will depend on individual differences in math anxiety. Both the individual components and the aggregate of the current dissertation provide substantial contributions to the math anxiety literature in hopes of meaningfully impacting future work aimed at improving student learning experiences and outcomes.

References

Abramowitz, J. S., Deacon, B. J., & Whiteside, S. P. (2012). *Exposure therapy for anxiety: Principles and practice.* Guilford Press.

Ackerman, R., & Thompson, V. A. (2017). Meta-reasoning: Monitoring and control of thinking and reasoning. *Trends in Cognitive Sciences*, *21*(8), 607-617.

Alexander, L., & Martray, C. (1989). The development of an abbreviated version of the Mathematics Anxiety Rating Scale. *Measurement and Evaluation in Counseling and Development*, *22*(3), 143–150.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current directions in psychological science*, *11*(5), 181-185.

Ashcraft, M. H., & Faust, M. W. (1994). Mathematics anxiety and mental arithmetic performance: An exploratory investigation. *Cognition & Emotion*, *8*(2), 97–125.

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.

Barron, K. E., & Hulleman, C. S. (2015). Expectancy-value-cost model of motivation. *Psychology*, *84*, 261-271.

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*.

Beilock, S. L., & Carr, T. H. (2005). When high-powered people fail: Working memory and "choking under pressure" in math. *Psychological science*, *16*(2), 101-105.

Brush, L. R. (1978). A Validation Study of the Mathematics Anxiety Rating Scale (Mars. *Educational and Psychological Measurement*, *38*(2), 485-499.

Cacioppo, J. T., & Petty, R. E. (1982). The need for cognition. *Journal of personality and social psychology*, *42*(1), 116.

Carey, E., Hill, F., Devine, A., & Szücs, D. (2016). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Frontiers in Psychology*, *6*, 1987.

Chen, P., Chavez, O., Ong, D. C., & Gunderson, B. (2017). Strategic resource use for learning: A self-administered intervention that guides self-reflection on effective resource use enhances academic performance. *Psychological Science*, *28*(6), 774–785.

Chong, T. J., Bonnelle, V., & Husain, M. (2016). Quantifying motivation with effort-based decision-making paradigms in health and disease. In *Progress in brain research* (Vol. 229, pp. 71-100). Elsevier.

Choe, K. W., Jenifer, J. B., Rozek, C. S., Berman, M. G., & Beilock, S. L. (2019). Calculated avoidance: Math anxiety predicts math avoidance in effort-based decision-making. *Science Advances*, *5*(11), 1–10.

College Board. (2019). AP Exam Scores. Retrieved from https://aphighered.collegeboard.org/courses-exams/scoring

College Board. (2018). Student Score Distributions. Retrieved from https://secure-media.collegeboard.org/digitalServices/pdf/research/2018/Student-Score-Distributions-2018.pdf

Crowne, D. P., & Marlowe, D. (1960). A new scale of social desirability independent of psychopathology. *Journal of consulting psychology*, *24*(4), 349.

D'Ailly, H., & Bergering, A. J. (1992). Mathematics anxiety and mathematics avoidance behavior: A validation study of two MARS factor-derived scales. *Educational and Psychological Measurement*, *52*(2), 369-377.

De Bock, D., Deprez, J., Van Dooren, W., Roelens, M., & Verschaffel, L. (2011). Abstract or concrete examples in learning mathematics? A replication and elaboration of Kaminski, Sloutsky, and Heckler's study. *Journal for research in Mathematics Education*, *42*(2), 109-126.

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.

DiFrancesca, D., Nietfeld, J. L., & Cao, L. (2016). A comparison of high and low achieving students on self-regulated learning variables. *Learning and Individual Differences*, *45*, 228-236.

Dowker, A., Sarkar, A., & Looi, C. Y. (2016). Mathematics anxiety: What have we learned in 60 years?. *Frontiers in psychology*, *7*, 508.

Dunlosky, J., Rawson, K. A., Marsh, E. J., Nathan, M. J., & Willingham, D. T. (2013). Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest, Supplement*, *14*(1), 4–58.

Dutton, W. H. (1951). Attitudes of prospective teachers toward arithmetic. *The Elementary School Journal*, *52*(2), 84-90.

Eccles (Parsons), J., Adler, T. F., Futterman, R., Goff, S. B., Kaczala, C. M., Meece, J. L., & Midgley, C. (1983). Expectancies, values, and academic behaviors. In J. T. Spence (Ed.), Achievement and achievement motivation (pp. 75–146). San Francisco, CA: W. H. Freeman.

Faust, M. W. (1992). Analysis of physiological reactivity in mathematics anxiety. Unpublished doctoral dissertation, Bowling Green State University, Ohio.

Faust, M. W., Ashcraft, M. H., & Fleck, D. E. (1996). Mathematics Anxiety Effects in Simple and Complex Addition. *Mathematical Cognition*, *2*(1), 25-62.

Flake, J. K., Barron, K. E., Hulleman, C., McCoach, B. D., & Welsh, M. E. (2015). Measuring cost: The forgotten component of expectancy-value theory. *Contemporary Educational Psychology*, *41*, 232-244.

Fleming, S. M., Weil, R. S., Nagy, Z., Dolan, R. J., & Rees, G. (2010). Relating introspective accuracy to individual differences in brain structure. *Science*, *329*(5998), 1541-1543

Foley, A. E., Herts, J. B., Borgonovi, F., Guerriero, S., Levine, S. C., & Beilock, S. L. (2017). The Math Anxiety-Performance Link: A Global Phenomenon. *Current Directions in Psychological Science*, *26*(1), 52–58.

Frederick, S. (2005). Cognitive reflection and decision making. *Journal of Economic perspectives*, *19*(4), 25-42.

Gyurak, A., Gross, J. J., & Etkin, A. (2011). Explicit and implicit emotion regulation: a dual-process framework. *Cognition and emotion*, *25*(3), 400-412.

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

Jansen, B. R. J., Louwerse, J., Straatemeier, M., Van der Ven, S. H. G., Klinkenberg, S., and Van der Maas, H. L. J. (2013). The influence of experiencing success in math on math anxiety, perceived math competence, and math performance. Learn. Individ. Differ. 24, 190–197.

Jiang, Y., Rosenzweig, E. Q., & Gaspard, H. (2018). An expectancy-value-cost approach in predicting adolescent students' academic motivation and achievement. *Contemporary Educational Psychology*, *54*, 139-152.

Kaminski, J. A., Sloutsky, V. M., & Heckler, A. F. (2008). The advantage of abstract examples in learning math. *Science,* 320, 454–455

Karpicke, J. D., Butler, A. C., & Roediger, H. L. (2009). Metacognitive strategies in student learning: Do students practise retrieval when they study on their own? *Memory*, *17*(4), 471–479.

Kelly, W. P., & Tomhave, W. K. (1985). A study of math anxiety/math avoidance in preservice elementary teachers. *The Arithmetic Teacher*, *32*(5), 51-53.

Kornell, N., Hays, M. J., & Bjork, R. A. (2009). Unsuccessful retrieval attempts enhance subsequent learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(4), 989.

Kosovich, J. J., Hulleman, C. S., Barron, K. E., & Getty, S. (2015). A practical measure of student motivation: Establishing validity evidence for the expectancy-value-cost scale in middle school. *The Journal of Early Adolescence*, *35*(5-6), 790-816.

LeFevre, J. A., Kulak, A. G., & Heymans, S. L. (1992). Factors influencing the selection of university majors varying in mathematical content. *Canadian Journal of Behavioural Science*, *24*(3), 276–289.

Leppink, J., Paas, F., Van Gog, T., van Der Vleuten, C. P., & Van Merrienboer, J. J. (2014). Effects of pairs of problems and examples on task performance and different types of cognitive load. *Learning and Instruction*, *30*, 32-42.

Lowe, C., & Rabbitt, P. (1998). Test\re-test reliability of the CANTAB and ISPOCD neuropsychological batteries: theoretical and practical issues. *Neuropsychologia*, *36*(9), 915-923.

Lyons, I. M., & Beilock, S. L. (2012). When math hurts: math anxiety predicts pain network activation in anticipation of doing math. *PloS One*, *7*(10), e48076.

Ma, X. (1999). A meta-analysis of the relationship between anxiety toward mathematics and achievement in mathematics. *Journal for research in mathematics education*, 520-540.

Ma, X., & Xu, J. (2004). The causal ordering of mathematics anxiety and mathematics achievement: A longitudinal panel analysis. *Journal of Adolescence*, 27(2), 165–79.

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.

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), 102939.

Meece, J. L., Parsons, J. E., Kaczala, C. M., & Goff, S. B. (1982). Sex differences in math achievement: Toward a model of academic choice. *Psychological Bulletin*, *91*(2), 324.

Meece, J. L., Wigfield, A., & Eccles, J. S. (1990). Predictors of math anxiety and its influence on young adolescents' course enrollment intentions and performance in mathematics. *Journal of educational psychology*, *82*(1), 60.

Midgley, C., Maehr, M. L., Hruda, L. Z., Anderman, E., Anderman, L., Freeman, K. E., & Urdan, T. (2000). Manual for the patterns of adaptive learning scales. Ann Arbor: University of Michigan.

Morsanyi, K., Busdraghi, C., & Primi, C. (2014). Mathematical anxiety is linked to reduced cognitive reflection: A potential road from discomfort in the mathematics classroom to susceptibility to biases. *Behavioral and Brain Functions*, *10*(1).

Morsanyi, K., Cheallaigh, N. N., & Ackerman, R. (2019). Mathematics anxiety and metacognitive processes: Proposal for a new line of inquiry. *Psihologijske teme*, *28*(1), 147-169.

Necka, E. A., Sokolowski, H. M., & Lyons, I. M. (2015). The role of self-math overlap in understanding math anxiety and the relation between math anxiety and performance. *Frontiers in psychology*, *6*, 1543.

Núñez-Peña, M. I., Guilera, G., & Suárez-Pellicioni, M. (2014). The single-item math anxiety scale: An alternative way of measuring mathematical anxiety. *Journal of Psychoeducational Assessment*, *32*(4), 306-317.

OECD. (2013a). PISA 2012 results: Ready to learn: Students' engagement, drive and self-beliefs (Vol. III). Paris, France.

OECD. (2013b). OECD skills outlook 2013: First results from the survey of adult skills. Paris, France.

Padoa-Schioppa, C. (2011). Neurobiology of economic choice: a good-based model. *Annual review of neuroscience*, *34*, 333-359.

Piper, B. J., Mueller, S. T., Geerken, A. R., Dixon, K. L., Kroliczak, G., Olsen, R. H., & Miller, J. K. (2015). Reliability and validity of neurobehavioral function on the Psychology Experimental Building Language test battery in young adults. *PeerJ*, *3*, e1460.

Pintrich, P. R. (1991). A manual for the use of the Motivated Strategies for Learning Questionnaire (MSLQ).

Pintrich, P. R., & De Groot, E. V. (1990). Motivational and Self-Regulated Learning Components of Classroom Academic Performance. *Journal of Educational Psychology*, *82*(1), 33–40.

Pizzie, R. G., & Kraemer, D. J. M. (2017). Avoiding math on a rapid timescale: Emotional responsivity and anxious attention in math anxiety. *Brain and Cognition*, *118*, 100–107.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods*, *40*(3), 879–891.

Preuschoff, K., Bossaerts, P., & Quartz, S. R. (2006). Neural differentiation of expected reward and risk in human subcortical structures. *Neuron*, *51*(3), 381-390.

Proctor, B. E., Prevatt, F. F., Adams, K. S., Reaser, A., & Petscher, Y. (2006). Study Skills Profiles of Normal-Achieving and Academically-Struggling College Students. *Journal of College Student Development*, *47*(1), 37–51.

Ramirez, G., & Beilock, S. L. (2011). Writing about testing worries boosts exam performance in the classroom. *Science*, *331*(6014), 211-213.

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.

Ramirez, G., Shaw, S. T., & Maloney, E. A. (2018). Math anxiety: Past research, promising interventions, and a new interpretation framework. *Educational Psychologist*, *53*(3), 145–164.

Richardson, F. C., & Suinn, R. M. (1972). The mathematics anxiety rating scale: psychometric data. *Journal of Counseling Psychology*. *19(6)*, 551.

Richland, L. E., Naslund-Hadley, E., Alonzo, H., Lyons, E., & Vollman, E. (2020). Teacher and Students' Mathematics Anxiety and Achievement in a Low-Income National Context. *Mind, Brain, and Education*.

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a rational and mechanistic account of mental effort. *Annual review of neuroscience*, *40*, 99-124.

Spielberger, C.D. (1983). STAI State-trait Anxiety Inventory for Adults Form Y: Review Set ; Manual,Test, Scoring Key.

Spielberger, C.D. (1980). Test Anxiety Inventory: “Test Attitude Inventory”

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.

Talmi, D., Dayan, P., Kiebel, S. J., Frith, C. D., & Dolan, R. J. (2009). How humans integrate the prospects of pain and reward during choice. *Journal of Neuroscience*, *29*(46), 14617-14626.

Trafton, J. G., & Reiser, B. J. (1993). Studying examples and solving problems: Contributions to skill acquisition. In *Proceedings of the 15th conference of the Cognitive Science Society. Citeseer* (pp. 1017-1022).

Treadway, M. T., Bossaller, N. A., Shelton, R. C., & Zald, D. H. (2012). Effort-based decision-making in major depressive disorder: a translational model of motivational anhedonia. *Journal of abnormal psychology*, *121*(3), 553.

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.

Weller, J. A., Dieckmann, N. F., Tusler, M., Mertz, C. K., Burns, W. J., & Peters, E. (2013). Development and testing of an abbreviated numeracy scale: A Rasch analysis approach. *Journal of Behavioral Decision Making*, *26*(2), 198-212.

Weinberger, D. A., Schwartz, G. E., & Davidson, R. J. (1979). Low-anxious, high-anxious, and repressive coping styles: psychometric patterns and behavioral and physiological responses to stress. *Journal of abnormal psychology*, *88*(4), 369.

Westbrook, A., Kester, D., & Braver, T. S. (2013). What is the subjective cost of cognitive effort? Load, trait, and aging effects revealed by economic preference. *PloS one*, *8*(7), e68210.

Yip, M. C. W. (2007). Educational Psychology Differences in Learning and Study Strategies between High and Low Achieving University Students: A Hong Kong study. *Educational Psychology*, *27*(5), 597–606.

Young, C. B., Wu, S. S., & Menon, V. (2012). The neurodevelopmental basis of math anxiety. *Psychological science*, *23*(5), 492-501.

APPENDIX A: Links to Additional Material for Study 1

Preregistration: https://osf.io/9vpgm/

Materials, Data and Analysis Scripts: https://osf.io/t4wju/

Supplemental Materials: http://advances.sciencemag.org/cgi/content/full/5/11/eaay1062/DC1

APPENDIX B: Supplementary Materials for Study 2

Table 3. *Zero-Order Correlations Between All Study Variables*

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Math anxiety															
2. AP Calculus Exam Score	-.27**														
3. Time Allocation: reading the textbook (1st time)	.21**	-.16*													
4. Time Allocation: re-reading textbook	.08	-.18*	.27**												
5. Time Allocation: Reviewing homework solutions	.15*	.10	-.01	.00											
6. Time Allocation: Solving Practice Problems	-.28**	.35**	-.33**	-.35**	-.29**										
7. Time Allocation: Reading examples of solved problems	.06	-.22**	-.13	-.16	-.13	-.27**									
8. Time Allocation: Reviewing Notes	.02	-.07	-.21**	-.22**	-.27**	-.38**	-.13								
9. Effort Ranking: Reading the textbook for the first time	.04	.02	-.15*	.03	.12	-.06	.07	.02							
10. Effort Ranking: re-reading textbook sections	.17*	.01	-.10	.03	.10	-.09	.02	.07	.51**						
11. Effort Ranking: Reviewing homework solutions	-.10	.02	.00	-.07	-.22	.17*	-.02	.01	-.43**	-.35**					
12. Effort Ranking: Solving practice problems	-.15	-.08	.13	.04	-.04	.06	-.06	-.10	-.43**	-.61**	.009				
13. Effort Ranking: Reading examples of solved problems	-.04	.05	.15*	-.14	-.13	.05	-.08	.08	-.51**	-.36**	.01	.16*			
14. Effort Ranking: Reviewing notes	.02	-.01	.03	.08	.08	-.06	.03	-.08	-.52**	-.50**	.07	.13	-.07		
15. Effort Prioritization	-.22**	.22**	.07	-.05	-.07	.21**	-.18*	-.08	.03	-.01	-.02	.10	-.06	-.03	

Note. N = 190. * $p < .05$; ** $p < .01$

Individual Mediation Models

In addition to the multiple mediator model presented in the main manuscript, we also estimated two separate individual mediator models that assessed practice problem quantity and quality as singular mediators of the association between math anxiety and exam performance. Using the same bootstrapping procedures as in the multiple mediator model in the main manuscript, we tested two models: (1) does practice problem quantity mediate the association between math anxiety and exam performance and (2) does practice problem quality mediate the association between math anxiety and exam performance?

We found evidence that both practice problem quantity and quality individually mediated the association between math anxiety and exam performance. Specifically, we found a significant indirect effect of math anxiety on exam performance through practice problem quantity ($\beta = -.08$, $SE = .03$, 95% CI [-.14, -.03]. Additionally, we found a significant indirect effect of math anxiety on exam performance through practice problem quality ($\beta = -.04$, $SE = .02$, 95% CI [-.09, -.01]).

APPENDIX C: Supplementary Materials for Study 3

Table 4. *Zero-Order Correlations Between All Study Variables*

Variable		1	2	3	4	5	6	7	8	9
1.	**Math Anxiety**									
2.	**Test anxiety**	.78**								
3.	**Trait Anxiety**	.32**	.49**							
4.	**Math ability**	-.60**	-.47**	-.08						
5.	**Easy practice problem choice**	-.07	-.06	-.01	.07					
6.	**Hard practice problem choice**	.00	.03	.11*	.03	.79**				
7.	**Easy practice problem accuracy**	-.47**	-.38**	-.06	.55**	-.02	.02			
8.	**Hard practice problem accuracy**	-.43**	-.29**	.01	.54**	-.05	.07	.63**		
9.	**Test performance**	-.56**	-.44**	-.08	.68**	.05	.07	.74**	.69**	

Note. N = 358. * $p < .05$; ** $p < .01$

Individual Mediation Models

Easy accuracy mediation. The total standardized effect of math anxiety on test performance was -.23, $p < .001$. The standardized direct effect of math anxiety on test performance was -.13, $p = .02$. The bootstrapped standardized indirect effect for easy accuracy was -.10, 95%CI [-.18, -.02). Our bootstrap process also found that the proportion mediated by easy accuracy was 43%, $p = .006$.

Hard accuracy mediation. The total standardized effect of math anxiety on test performance was -.23, $p = .001$. The standardized direct effect of math anxiety on test performance was -.12, $p = .04$. The bootstrapped standardized indirect effect for hard accuracy was -.11, 95% CI [-.18, -.04). Our bootstrap process also found that the proportion mediated by hard accuracy was 47%.

Figure 11. *Relation Between Math Anxiety & Test Performance by Order & Schedule*