The Influence of Individual Differences in Math Anxiety on Learning Novel Mathematics Content

by

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DEDICATION

This dissertation is dedicated to my parents, Farid Ibrahim and Laila Elhalawani for instilling in me my desire for learning and growth.

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ABSTRACT

Women are vastly underrepresented in science, technology, engineering, and mathematics careers, and one contributing factor is math anxiety. Previous research finds that math anxiety is negatively associated with math performance and achievement, and positively associated with avoidance of math intensive fields. However, our current understanding of the influence of math anxiety on learning of new math knowledge is lacking. To develop interventions that mitigate the negative effects of math anxiety, we need to have a better understanding of the influence of math anxiety on learning of new math content and its interaction with common study strategies. If math anxiety only influences performance of math knowledge, future interventions would need to focus on mitigating the depressing effect of math anxiety on performance, but if math anxiety also interferes with learning of new math information, future interventions would also need to address strategies to improve mastery of math information for individuals with high math anxiety.

The current dissertation aims to 1) determine the extent to which math anxiety interferes with learning of new math content, 2) determine if some study strategies lead to different learning outcomes based on individual differences in math anxiety and general math skill, and 3) determine if individuals with high math anxiety use different study strategies than individuals with low math anxiety. To address aims 1 and 2, we ran three experimental studies. Participants were randomly assigned to study a novel math procedure either with examples or by completing practice problems and completed measures of math anxiety and math skill. We found consistent evidence across the first three studies that individuals with math anxiety tend to have lower

learning outcomes than their less anxious counterparts, above and beyond their math skill (aim 1). In contrast, the effects of studying with either examples or practice problems for individuals with low math skill and high math anxiety were less robust (aim 2). In study 1, we found that individuals with low math skill had lower learning outcomes when studying examples compared to completing practice problems. In study 3, we found that individuals with high math anxiety had lower learning outcomes when completing practice problems compared to studying examples. To address aim 3, participants who had recently taken a quantitative course completed a survey assessing their math anxiety and use of effective and less effective study habits (based on the existing literature; e.g. self-testing versus rereading). We found that individuals with high math anxiety reported increased use of study strategies seen as ineffective and decreased use of study strategies thought to be more effective for learning based on previous literature.

Our findings suggest that one reason that math anxious women might be opting out of higher STEM education is because they are having difficulty mastering the required math coursework. Future interventions for math anxiety should focus on increasing mastery of math material and encouraging the use of evidence-based study strategies. However, much more research is needed to further understand the way in which math anxiety interferes with learning of new math content.

CHAPTER I

Introduction

Careers in science, technology, engineering, and mathematics (STEM) are the backbone of modern society. These fields are influence every aspect of our everyday lives from our health to our homes. The United States Bureau of Labor Statistics projects that STEM jobs will increase dramatically in the coming years (Vilorio, 2014), making it increasingly important to encourage students to pursue STEM education. However, women and non-Asian minorities are considerably underrepresented in STEM fields of study and the workforce (Musu-Gillette et al., 2017). The representation of women and non-Asian minorities is lowest in engineering, mathematics, and the physical sciences; areas that heavily rely on upper-level mathematics coursework. Math anxiety is one known factor that leads many, especially women, to turn away from much of STEM education, likely due to the large amount of upper-level mathematics coursework involved (Ashcraft & Kirk, 2001; Hackett, 1985; Hembree, 1990).

Math anxiety is commonly defined as “a feeling of tension and anxiety that interferes with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations,” (Richardson & Suinn, 1972, p. 551) or “feeling of tension, apprehension or even dread, that interferes with the ordinary manipulation of numbers and the solving of mathematical problems,” (Ashcraft & Faust, 1994, p. 98), among other variations upon the theme. Math anxiety is associated with lower math performance and achievement, negative attitudes towards math, lower confidence in one’s math ability, and a decrease in the perception of the utility of math (Ashcraft & Kirk, 2001; Hembree, 1990; Xin

Ma, 1999; Wigfield & Meece, 1988). Such negativity leads many to avoid the subject, taking less math in K-12, and opting out of career paths that require math coursework beyond what is required to graduate from high school or enter college (Ashcraft, Krause, & Hopko, 2007; Ashcraft & Moore, 2009; Hackett, 1985; Hembree, 1990).

The last 60 or so years of research has demonstrated that math anxiety poses a significant obstacle to individuals' math achievement, and persistance (Ashcraft & Faust, 1994; Ashcraft & Krause, 2007; Foley et al., 2017; Hembree, 1990; Ho et al., 2000; Xin Ma, 1999; M. I. Núñez-Peña, Suárez-Pellicioni, & Bono, 2013; Ramirez, Gunderson, Levine, & Beilock, 2013; Wigfield & Meece, 1988), but the nature of the obstacle it poses is still largely not understood. Some evidence suggests that math anxiety merely depresses individuals' performance. Such that individuals with high math anxiety have largely intact basic math knowledge, but their math anxiety burdens their cognitive resources or interferes with basic attention processes, which in turn interferes with mathematical performance, termed the "affective drop" (Ashcraft & Moore, 2009). However, to my knowledge, the vast majority of the existing work has only focused on pre-existing mathematical knowledge. Do individuals with high math anxiety master new information as well as their less-anxious counterparts? Or do they have a more challenging time? Current evidence can only speak to how math anxiety interferes with the production of already existing knowledge. No evidence currently exists on the nature of the obstacle math anxiety imposes on learning of new mathematical content.

This dissertation will focus on assessing the extent to which math anxiety interferes with learning of new math content, above and beyond its influence on performance of existing math skill. I operationalize learning of math procedures as the process of gaining fluency and automatization of the procedure. During learning or even re-learning (the case when a procedure was learned in the past but not currently remembered), the individual has not mastered the new material for they are still in the process of creating or strengthening the schema of the procedure. Once that schema is well established, the individual will be fluent and have fully automatized the new procedure, suggesting the information is fully learned. For these reasons, learning new information is more cognitively demanding than producing already existing knowledge. Considering that math anxiety is known to interfere with basic cognitive processes, it is possible that the deleterious effects of math anxiety are magnified when learning new content, making it more difficult for individuals with high math anxiety to acquire new content. However, it is also possible that individuals with math anxiety acquire new information just as well as their less-anxious peers but merely perform less well on measures assessing that learning. The former could have more profound consequences for one's decisions on future STEM education than the latter, considering one of the most important predictors of future STEM degree completion for high school seniors is previous math achievement and coursework (Maltese & Tai, 2011). I know that individuals with higher math anxiety opt out of higher math courses more than their less anxious counterparts (Hembree, 1990), but I currently do not have a clear understanding of why. If learning of new math information is more difficult for individuals with high math anxiety than their less-anxious counterparts, this would require us to focus interventions on improving content learning. In contrast, if math anxiety merely depresses performance but does not interfere with learning, interventions should be more focused on decreasing the negative effects of math anxiety on performance. It is important to know the extent to which math anxiety interferes with learning of new math material so that I can develop techniques that facilitate learning and reduce avoidance for individuals with high math anxiety.

Before I delve into these new questions, I will present more background on what I currently know about math anxiety. In the current chapter, I will present a detailed summary of the current research on math anxiety from its relations to trait and test anxiety, neural correlates, hypothesized causes, etc. to what I currently know about its potential mechanisms.

Math Anxiety: Its Known Correlates

To date we have learned a considerable amount about math anxiety and its relation to other anxiety measures, neural activity, math performance/achievement, attitudes towards math, age, working memory, and inhibitory control [for a comprehensive review of the math anxiety literature please see Chang & Beilock, 2016; Dowker, Sarkar, & Looi, 2016; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2016]. Modern interest in math anxiety began in the 1950s, after a teacher noted her students' struggle with math (Ashcraft & Moore, 2009; Gough, 1954) and Dreger and Aiken (1957) addressed "numerical anxiety" in an article and added math anxiety items into the Taylor Manifest Anxiety Scale (cf. Ashcraft & Moore, 2009). During the late 1950s through the 1960s, there was increased interest in studying specific types of anxiety and their specific effects on performance in particular domains (Richardson & Suinn, 1972). Richards & Suinn (1972) developed the first widely used, validated measure of math anxiety, the 98-item Math Anxiety Rating Scale (MARS). In the MARS, individuals are to use a 5-point Likert scale to indicate how anxious they feel in various math related situations (e.g. "thinking about an upcoming math test 1 day before"). The MARS has been further updated into more current scales such as the 25-item shortened MARS (sMARS; Alexander & Martray, 1989) and the 9-item Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003). Several other math anxiety scales have also been developed, including ones adapted for use in children [see Suarez-Pellicioni et al., (2016, p. 4) for a list]. Math anxiety is moderately related to test anxiety (*r* = 0.52) and general anxiety (*r* = 0.35; Hembree, 1990). However, math anxiety measures are more highly correlated with each other than with measures of test anxiety or general anxiety (Ashcraft & Ridley, 2005; Dew, Galassi, & Galassi, 1984; Hembree, 1990). Let us consider the correlation between math anxiety and test anxiety reported in Hembree (1990), *r* = 0.52, that means only 27% of the variance between math anxiety and test anxiety is shared. In addition, measures of math anxiety are better predictors of math performance than test anxiety measures (Ashcraft & Faust, 1994), and they only predict performance on math but not verbal tasks (Hembree, 1990). The little variance shared between math anxiety and test anxiety makes sense when the measures are compared. Math anxiety items assess more than anxiety towards testing situations. such as assessing anxiety while completing math homework or while watching teachings explain a topic. Just on the basis of the items, one can demonstrate math anxiety without necessarily demonstrating test anxiety more generally. In sum, math anxiety is generally accepted as an independent construct with unique predictive power of math related outcomes than measures of test or general anxiety.

Math Anxiety and Math Performance/Achievement

As mentioned previously, math anxiety is generally found to be negatively associated with math performance and achievement. The Hembree (1990) meta-analysis found the correlation between math anxiety and math achievement/performance to range from -0.27 to -0.34 based on the outcome measure and year in school; the Ma (1999) meta-analysis found an overall correlation between math anxiety and achievement to be -0.27. Although a correlation of -0.27 means that only 7.29% of the variance in math performance is accounted for by math anxiety, such an effect could mean the difference between a student receiving B or a C. A student receiving a B in a math course is likely to make very different decisions about whether they will take future math courses than if they had received a C. The math anxiety-performance link seems to be a worldwide phenomenon, although the strength of the relationship varies between countries (Foley et al., 2017; Ho et al., 2000; Lee, 2009). Even though most of this work had been done in young adults, a subset of studies also demonstrate that math anxiety negatively affects math performance for young children (Ramirez et al., 2013; Vukovic, Kieffer, Bailey, & Harari, 2013; Wu, Barth, Amin, Malcarne, & Menon, 2012). Math anxiety has generally been found to be higher in women than in men, despite that, in general, there is no gender gap in mathematics achievement, except for when we assess the top echelons of performance (Devine, Fawcett, Szűcs, & Dowker, 2012; Else-Quest, Hyde, & Linn, 2010; Hembree, 1990; Xin Ma, 1999; Wigfield & Meece, 1988). According to Ashcraft & Moore (2009, p. 201), "Math-anxious individuals avoid taking math courses whenever possible, avoid selecting courses of study in college that involve math, and of course avoid career paths that involve math." Such avoidance behaviors could be a reason that women are so underrepresented in math-intensive STEM fields, such as technology and engineering. We know that, in general, math anxiety is negatively associated with general math performance (e.g. basic math, algebra, etc.). However, it is currently unclear as to whether math anxiety leads to poor math performance and achievement, if poor math performance and numerical knowledge lead to math anxiety, or if the two have more of a bidirectional relationship.

Some evidence suggests that math anxiety only negatively influences performance on more complex/cognitively demanding mathematics procedures, such as two-digit mental addition with a carry operation. Ashcraft & Faust (1994) had undergraduate students complete a mental arithmetic verification task as well as a math anxiety questionnaire. They found for simple arithmetic problems (e.g. single-digit addition or multiplication) there was no differential effect of math anxiety. For complex arithmetic (e.g. two-digit mental addition with a carry operation), individuals with higher math anxiety, based on quartiles of the MARS scores, were significantly slower and made more errors than those with lower math anxiety. These results suggest that the effects of math anxiety are not apparent in well learned/memorized numerical knowledge such as single digit addition but are more likely to interfere with processing on more cognitively demanding/less automatized problems. Additional studies also support this finding (Ashcraft & Kirk, 2001; Ashcraft & Krause, 2007; Faust et al, 1996). However, it seems that even the negative effects of math anxiety on complex and cognitively demanding arithmetic might be context dependent. Faust et al. (1996) found that the performance differences between individuals with high and low math anxiety on complex arithmetic diminished when the test was not timed. These findings suggest that it is not that individuals with high math anxiety have low math knowledge, but that math anxiety leads to a decline in performance, especially in high pressure situations, termed the “affective drop” (Ashcraft & Moore, 2009).

In contrast, some research has suggested that math anxiety is related to differences in basic-level numerical abilities. Maloney, Risko, Ansari, & Fugelsang (2010), had individuals complete a visual enumeration task, measure of working memory, and math anxiety scale. The visual enumeration task presented displays consisting of multiple objects to which the subjects would have to identify the number presented. Displays of 1-4 items generally have fast reaction times and accurate responses, termed “subitizing”, while displays of 5 or more objects generally consist of slower reactions times and lower accuracy, termed “counting”. Performance on such a task is generally seen as an indicator for numerical processing. Maloney et al. (2010) found that individuals with high math anxiety (top quartile of math anxiety scores) performed significantly worse than individuals with low math anxiety (bottom quartile) on counting trials but not on subitizing trials. The authors interpreted this result as being partly in opposition to Ashcraft's findings, that math anxiety only affects complex mathematical tasks, since individuals with high math anxiety were significantly worse on counting (a basic numerical task) compared to those with low math anxiety. The authors also suggested that these findings demonstrate that individuals with high math anxiety might have a low-level numerical deficit. However, I do not necessarily think that these findings suggest that individuals with high math anxiety have a low-level numerical deficit. The counting trials (5+ items) are more cognitively demanding than the subitizing trials. Human working memory (the mental workspace used to store and manipulate information on-line) is very limited in capacity; in-fact five items would be considered a considerable working memory load for most individuals (Miyake & Shah, 1999; Sweller, Merrienboer, & Paas, 1998). Indeed, Maloney et al. (2010) found that the effects between high and low math anxious individuals disappeared when controlling for working memory capacity. Therefore, the decrease in math performance associated with math anxiety could still be accounted for by the "affective drop" described by Ashcraft & Moore (2009) and not necessarily from a low-level numerical deficit in individuals with high math anxiety.

Further exploring the potential for a low-level numerical deficit in individuals with high math anxiety, Maloney, Ansari, & Fugelsang, (2011) explored symbolic magnitude processing for individuals with high and low math anxiety. Participants were presented with a number ranging from 1-4 or 6-9 and were to indicate whether the presented number was higher or lower than 5, completing 160 trials. The outcome measure of interest was the numerical distance effect, a phenomenon in which the numerical distance is inversely related to reaction time (Dehaene, Dupoux, & Mehler, 1990). For example, when judging which is the larger of two numbers, individuals will respond more quickly when comparing 1 to 9 than when comparing 8 to 9.

Maloney and colleagues (2011) found that individuals with high math anxiety (top quartile) had a significantly larger numerical distance effect than individuals with low math anxiety (bottom quartile). That is, individuals with high math anxiety were much slower to respond to trials with smaller distances than to larger differences and were overall slower than individuals with low math anxiety. The authors state that there is no evidence to suggest that numerical comparison task is particularly cognitively demanding, therefore, they claim that these findings do stand in contrast to Ashcraft's findings that math anxiety only negatively affects complex mathematical procedures. However, the authors do not point to any direct evidence as to the cognitive demand of numerical comparison tasks. According to Maloney et al. (2011), these findings suggest that individuals with high math anxiety might have a less precise understanding of numerical magnitude. Núñez-Peña & Suárez-Pellicioni (2014) also found a larger numerical distance effect in individuals with high math anxiety compared to those with low math anxiety. However, it is unclear as to whether a larger numerical distance effect necessarily implies a deficit in numerical representation or simply reflects other behavioral correlates of math anxiety, such as a lack of confidence in one's math ability. If one is less confident in their math ability, they are likely to experience more hesitation in responding, due to them second guessing their answers. There is some evidence to suggest that lower math self-efficacy is associated with slower reaction times in numerical tasks (Hoffman, 2010; Hoffman & Schraw, 2009; Hoffman & Spatariu, 2008). This could suggest more hesitation in responding in numerical comparison tasks, which could account for the larger numerical distance effect found in Maloney et al. (2011) and Núñez-Peña & Suárez-Pellicioni (2014) and not necessarily deficient numerical processing.

Two studies, to my knowledge, have attempted to directly explore the directional relationship between math anxiety and performance. Using data from a longitudinal panel study of students from 7th to 12th grade, Ma & Xu (2004) explored the directional relationship between math anxiety and achievement using structural equation modeling. Math achievement was assessed using four subscales measuring basic skills, algebra, geometry, and quantitative literacy. Math anxiety was assessed using two items on a five-point Likert-type scale: “doing mathematics often makes me nervous or upset,” and “I often get scared when I open my mathematics book and see a page of problems,” (Ma & Xu, 2004, p. 169). They found that prior math achievement was a significant predictor of future math anxiety, but that prior math anxiety was not a consistent predictor of future math achievement. Gender differences were also found; boys had stronger effects of prior math achievement predicting future math anxiety than did girls. There were no significant differences between genders in prior math anxiety predicting future math achievement. Ma & Xu (2004) provided some initial evidence that achievement leads to math anxiety but not vice versa. However, Ma & Xu (2004) only assessed these relationships starting from middle school. Ramirez et al. (2013) found evidence that math anxiety is apparent in as early as 1st grade, suggesting that elementary school math anxiety could predict future math achievement. However, in Ma & Xu (2004), math anxiety was not measured using a well validated scale such as the MARS, the lack of information on the reliability and the validity of these items measuring math anxiety make it difficult to interpret the directional findings with confidence. Recently, with a sample of 1st and 2nd grade children, Gunderson, Park, Maloney, Beilock, & Levine (2018) found that math achievement predicted later math anxiety, and although math anxiety predicted later achievement, it did so to a lesser extent, findings which support Ma & Xu’s (2004). It is also important to consider that other factors such as context could play an important role in the relationship between achievement and math anxiety, which I will discuss in greater detail later on. So far, these data suggest that previous achievement might be a more important predictor to future math anxiety than is math anxiety to future achievement, but with only two studies assessing the directionality between achievement and math anxiety, done more than a decade a part and in different age groups, it is still too early to say with any certainty whether this directionality holds.

In sum, there is a lack of longitudinal data available exploring the relationship between math anxiety and math performance, without which it is impossible to be confident in the direction of the relationship between math anxiety and performance. A bidirectional relationship also likely. Ashcraft et al. (2007) suggested that math anxiety and performance likely interact in a vicious cycle. Negative experiences with math lead to increases in math anxiety, which further leads to lower performance in math, increasing avoidance of the subject, and likely increasing math anxiety further [for a more in-depth discussion of the directional relationship between math anxiety and performance see Carey, Hill, Devine, & Szücs (2016)].

Neural correlates of math anxiety

In addition to behavioral correlates, recent research has begun to elucidate the neural correlates of math anxiety through functional magnetic resonance imaging (fMRI) and electroencephalogram (EEG)/event related potential (ERP) methodologies. Lyons & Beilock (2012a, 2012b) used fMRI to explore whether individuals with high math anxiety differed in their recruitment of brain regions compared to those with low math anxiety during an arithmetic verification task. Lyons and Beilock (2012b) found that in college students with high math anxiety, math anxiety score was associated with increased activity in bilateral dorso-posterior insula and mid-cingulate cortex during anticipation of a math task, but no such relationship was apparent in individuals with low math anxiety. The insula has often been implicated in threat and pain responses, the authors suggested that math anxious individuals view the anticipation of doing math as a painful or threatening experience. In Lyons and Beilock (2012a), they found that increased activity in frontoparietal regions during math task anticipation was associated with an increase in math performance for individuals with high math anxiety. These findings suggest that increased recruitment of regions associated with cognitive control act as a compensatory response to math anxiety, increasing math performance for individuals with high math anxiety.

Young, Wu, & Menon (2012) explored the neural correlates of math anxiety in 7 to 9-year-old children. They found that math anxiety was associated with increased activity in the right amygdala, a region implicated in processing of negative emotions. In addition, math anxiety was associated with decreased activity in posterior parietal and dorsolateral pre-frontal cortex during an arithmetic verification task, regions often implicated in working memory and mathematical reasoning. These findings suggest that in children, math anxiety is not associated with pain/threat perception as found in adults, but more so associated with aberrant processing of negative emotional stimuli. These studies provide us with an initial look into the brain regions implicated in math anxiety, demonstrating that math anxiety has physiological as well as behavioral effects within math contexts. However, these are the only three studies that have explored the brain regions implicated in math anxiety thus far. Additional work is needed for us to have a clear understanding of the brain regions implicated in math anxiety and its development over time.

In addition to fMRI work revealing some of the brain regions implicated in math anxiety, recent EEG/ERP work has begun to shed light on the patterns of neural activity associated with math anxiety. Suárez-Pellicioni, Núñez-Peña, & Colomé (2014) used ERPs to explore the neural activity patterns associated with math anxiety during a numerical Stroop task. They found that individuals with high math anxiety had a larger event-related negativity (ERN) when committing an error than individuals with low math anxiety. The ERN is a response locked ERP characterized by a negative deflection occurring 50 to 150 ms after the committence of an error, and it is generally interpreted as reflecting the affective response associated with error detection. The finding suggests that math anxiety is associated with a stronger affective response to making an error during math tasks. Núñez-Peña & Suárez-Pellicioni (2014) also found differential neural patterns between individuals with high and low math anxiety during a numerical magnitude comparison task. They found that individuals with high math anxiety had larger amplitude in ERP components associated with the numerical distance effect than did those with low math anxiety. In conjunction with the previously discussed findings from Maloney et al. (2011), that individuals with high math anxiety tend to have a larger numerical distance effect, Núñez-Peña & Suárez-Pellicioni (2014) suggested that this suggests that individuals with high math anxiety have a less precise numerical representation of magnitude than those with low math anxiety. The electrophysiological work done completed thus far, has demonstrated that there are several neural patterns in which individuals with high math anxiety differ from individuals with low math anxiety, providing additional physiological evidence of the effects of math anxiety. However, compared to the behavioral work that has been done, there is still much more research that needed for us to have a clear understanding of what these differential neural patterns between individuals with high and low math anxiety really mean in terms of mathematical processing.

Math Anxiety and Math Attitudes

Math anxiety does not only relate to math performance and achievement, but also relates to various attitudes towards math. High math anxiety is associated with lower math self-concept and self-efficacy, math interest, and perceptions of importance and usefulness of math, and is positively related to perceptions of difficulty and effort (Hembree, 1990; Jameson, 2014; Lee, 2009; Xin Ma, 1999). Self-concept and self-efficacy refer to one's evaluation either of oneself as a person (self-concept) or one's ability to perform a specific task (self-efficacy; Lee, 2009). Math self-concept and math self-efficacy refer to the individual's judgments, as defined above, specifically pertaining to mathematics. Math self-concept and self-efficacy are both related to math achievement and performance; the higher one's math self-concept or self-efficacy the higher their achievement and performance in math (Bong & Skaalvik, 2003; Cai, Viljaranta, & Georgiou, 2018; Lee, 2009; Pajares & Miller, 1994; Pajares & Schunk, 2001). Chen et al. (2018) found that young children's positive attitudes towards math predicted higher math performance above and beyond their age, general cognitive abilities, and math anxiety. However, the nature of the directional relationship between math self-efficacy/self-concept and math anxiety is still not well understood.

Meece, Wigfield, and Eccles (1990) found that in a group of 7th through 9th grade students, students' self-efficacy negatively predicted their math anxiety the following year. However, since math anxiety was not measured in the first round of data collection it is unclear whether math anxiety would have predicted their future self-efficacy. Ahmed, Minnaert, Kuyper, and van der Werf (2012) found reciprocal effects between math anxiety and math self-concept in 7th graders throughout an academic year, but that the directional effects of math anxiety on self-concept were half as strong. These findings suggest that math self-concept has more influence on future math anxiety than does math anxiety have on future math self-concept. Some propose that self-efficacy could serve as a compensatory mechanism in reducing the negative effects of math anxiety. Hoffman (2010) found that self-efficacy predicted math problem solving accuracy and efficiency for all problems, but that math anxiety was associated with reduced accuracy and efficiency for complex problems. According to the author, the perceived ease of the problem increased problem solving accuracy, but when problems were complex, the perceived ease of the problem declined, leading the individual to be more susceptible to the negative influence of math anxiety. However, much more research is necessary for us to pin down the nature of the relationship between math anxiety and math self-efficacy/self-concept.

Some research has further explored the relationship between math anxiety and other academic attitudes. Gunderson et al. (2018) found reciprocal effects between math achievement, math anxiety, and ability beliefs (whether intelligence, math and reading ability is fixed or malleable) in a group of 1st and 2nd grade children over a 6-month time-period, with one exception, initial math anxiety did not predict students' later ability beliefs. To elaborate, children's math achievement significantly predicted later math anxiety and ability beliefs, and although math anxiety and ability beliefs predicted future achievement they did so to a much lesser extent. In addition, ability beliefs predicted future math anxiety, but as stated previously, math anxiety did not predict later ability beliefs. Based on these findings, it could be that children's ability beliefs are a precursor to future math anxiety, such that children who believe that ability is fixed and are performance oriented are more susceptible to developing higher math anxiety in the future.

In summary, math anxiety seems to be closely related to the attitudes one holds about math as a domain. Some evidence suggests that one's attitudes towards math is a better predictor of future math anxiety than math anxiety is of future attitudes. Meaning, the attitudes young children develop towards math could have long term consequences for their math anxiety, math achievement, and career aspirations. However, directional evidence is still very limited, much more work is needed to understand why attitudes influence math anxiety and how the two factors interact to influence performance and achievement. There is some evidence to suggest that individuals' attitudes towards math and math anxiety are partially influenced by their social interactions and contexts in which they are exposed to math.

Development of Math Anxiety

Recent evidence has demonstrated children as young as 6 and 7 years old have some level of math anxiety (Ramirez et al., 2013; Vukovic et al., 2013; Wu et al., 2012). It also seems that math anxiety tends to increase with age until 9^{th} or 10^{th} grade, along with other negative attitudes towards mathematics, then leveling off afterwards (Gierl & Bisanz, 1995; Hembree, 1990; Wigfield & Meece, 1988).

The specific etiology of math anxiety is still unclear. Some reasons that have been explored are genetics (Wang et al., 2014), negative experiences in the classroom (Bekdemir, 2010; Turner et al., 2002), teacher attitudes towards math (Beilock, Gunderson, Ramirez, & Levine, 2010), and parent attitudes towards math (Maloney, Ramirez, Gunderson, Levine, & Beilock, 2015). Wang et al. (2014) found that 43% of the variance in math anxiety in twins was inherited while the remaining 57% was accounted for by non-shared environmental variables. These findings suggest that although there is some genetic predisposition to developing math anxiety, that specific experiences with math might play a larger role in the development of math anxiety. However, this is currently the only study assessing the heritability of math anxiety and much more evidence is needed to have a better understanding of the genetic factors involved.

Individuals often state negative experiences in math as the root of their math anxiety and avoidance (Ashcraft et al., 2007; Finlayson, 2014; Jackson & Leffingwell, 1999). Turner et al. (2002) explored the relationship between the classroom environment and students' avoidance behaviors in mathematics in ten sixth-grade classrooms. They found that students were less likely to use avoidance strategies (such as self-handicapping, avoidance of help-seeking, and avoiding novel approaches) in classrooms that were supportive and emphasized learning and understanding. In such classrooms, teachers often emphasized that learning is a process which sometimes includes making mistakes and asking questions. Students were more likely to report avoidance strategies when classrooms did not focus on building understanding and when there was low motivational support. Avoidance of mathematics is unlikely to lead students to think positively about the subject, and more likely to lead students to develop negative attitudes which may exacerbate math anxiety. Bekdemir (2010) explored the relationship between math anxiety and past negative math classroom experiences in pre-service teachers. They found that past negative classroom experiences in math were significantly related to the individuals reported math anxiety. Reported negative experiences were mostly related to hostile instructor behavior, exam anxiety, and perception of content difficulty. However, due to the retrospective nature of the negative experiences being reported, it is possible that individuals with high math anxiety are more likely to remember negative experiences with mathematics than those with lower math anxiety. Although it is still unclear how specific negative experiences with math influence later math anxiety, there is more evidence on how teacher and parent attitudes towards math can be transmitted down to younger individuals.

Teachers and parents play an important role in transmitting the value and importance of education to the next generation, however, negative attitudes towards certain domains can also be transmitted (Eccles & Jacobs, 1986; Eccles, Jacobs, & Harold, 1990; Stevenson et al., 1990). Math anxious teachers tend to create a classroom environment that emphasizes memorization and student's innate ability (Ramirez, Hooper, Kersting, Ferguson, & Yeager, 2018), likely leading students to develop negative, inflexible beliefs about the domain. Eccles & Jacobs (1986) found that teacher beliefs about student math abilities directly relate to student math self-concept and perception of task difficulty, and indirectly relates to future math achievement. Beilock et al. (2010) explored how female teacher math anxiety could influence young students (1^{st} and 2^{nd} grade) mathematics achievement through an academic year. They found that by the end of an academic year, teacher math anxiety was negatively related to girls', but not boys', math achievement. This relationship seemed to be mediated by the girls' gender ability beliefs, such that teacher math anxiety influences girls' gender ability beliefs which then predicted lower math achievement of girls at the end of the year. The authors suggest since only the girls that endorsed the belief "girls are not as good as boys in math" performed worse at the end of the year that it is not that math anxious teachers do not teach math well, but that teachers' feelings towards math are specifically being transmitted to these girls.

In high school, teacher math anxiety has been shown to influence both male and female students' math achievement. Ramirez et al. (2018) explored how teacher math anxiety influences student math achievement in 9^{th} grade, with a sample of teachers who specialize in teaching math. Overall, they found that teacher math anxiety was negatively related to student math achievement in 9^{th} grade, controlling for previous achievement. They also found that teacher math anxiety influences student achievement indirectly through two additional factors: use of effort and learning oriented teaching practices, and students' perceptions of their teacher's beliefs about intelligence. Teachers with higher math anxiety were less likely to use effort and learning oriented teaching practices in their classrooms, which are related to higher student achievement. In addition, students with teachers who have high math anxiety, were more likely to think that their teacher believes that intelligence is fixed, which is related to lower student achievement. Ramirez et al. (2018) suggest that teacher math anxiety leads to decreased student achievement because of the way in which they structure the learning context. Students often spend a whole academic year, taking one math course at a time. Spending an entire school year in a context that sends the message that math is difficult and only some people can be successful at it is demotivating and demoralizing.

In summary, these findings suggest that teachers play a role in shaping students' beliefs about their math abilities which could have long-term consequences for students' math achievement. However, there are no known studies to date which explore the direct or indirect link between teacher and student math anxiety which make it difficult to know if teacher math anxiety is transmitted to students. Despite this drawback, there is evidence that teacher beliefs influence students' ability perceptions, and we know that student ability perceptions are related to math anxiety, suggesting that teacher beliefs may have an indirect effect on student math anxiety, but much more work is needed to understand the role of teacher attitudes in the development of student math anxiety.

In addition to teacher's attitudes being transmitted to students, parents' beliefs also influence student math achievement and beliefs. Mothers' perception of child's math ability has been found to be directly related to child's perception of their own math ability (Eccles, Jacobs, & Harold, 1990). In addition, mother's perception of task difficulty for their child is directly associated with child's math anxiety and child's later math achievement (Eccles & Jacobs, 1986). Furthermore, children's perceptions of their parents' achievement goals in mathematics influence their own attitudes towards math (Friedel, Cortina, Turner, & Midgley, 2007). Is has also been found that parent involvement in preparing young children in math predicts their children's future math achievement (Miller, Kelly, & Zhou, 2004), although recent evidence suggests how it predicts future achievement might depend on the parents' own feelings towards the subject. Maloney et al. (2015) explored the effect of parent math anxiety on 1st and 2nd grade child math achievement. They found that children whose math anxious parents frequently helped them with math homework, had lower math achievement than those whose math anxious parents did not help them with homework and those whose parents were not math anxious. They also found that parents' math anxiety indirectly influenced children's math anxiety at the end of the academic year through the child's math achievement. These findings suggest that parents with high math anxiety have the potential to transmit their negative feelings towards mathematics to their children when frequently helping with math homework. However, much more work is needed for us to gain a clear understanding of how parents influence their children's math anxiety.

Math Anxiety: How it Works

So far, I have summarized much of the evidence on the correlates of math anxiety but have yet to discuss some of the hypothesized mechanisms through which math anxiety influences math performance and achievement. There are two main ways in which math anxiety is thought to impact math performance and achievement, overload of cognitive resources (processing efficiency theory; Eysenck & Calvo, 1992) and aberrant attentional control (attentional control theory; Eysenck, Derakshan, Santos, & Calvo, 2007). Both ideas are based on the separate but related literature on the cognitive consequences of state and trait anxiety. Processing efficiency theory is the predecessor of attentional control theory, so they are closely related.

Processing Efficiency Theory

Processing efficiency theory states that the worry associated with anxiety interferes with performance by overloading one's cognitive resources, specifically working memory (Eysenck & Calvo, 1992). Working memory is a mental workspace used to manipulate and store on-line information (Miyake & Shah, 1999). Working memory (WM) is a limited workspace that can only manage a handful of pieces of information at any one time (Sweller et al., 1998). According to processing efficiency theory, anxiety leads to an increase in worry (e.g. concern about performance on a task), worry consumes valuable working memory resources leading one to overload working memory resources, possibly leaving too few available to complete the task at hand, at least as long as the worries remain as occupants of WM space. Several studies have demonstrated that WM mediates the relationship between trait anxiety/worry and academic performance (Ganley & Vasilyeva, 2014; Owens, Stevenson, Norgate, & Hadwin, 2008). When the task is complex, worry overloads the WM system leading to a decline in performance (Eysenck & Calvo, 1992). For example, external pressure, which is thought to strain WM resources, has been shown to negatively influence math performance for cognitively demanding but not simple problems (Beilock & Carr, 2005; Beilock, Kulp, Holt, & Carr, 2004).

The same general process is hypothesized to occur when an individual has high math anxiety, as demonstrated by Trezise and Reeve (2016) discussed further below. Ashcraft and Faust (1994) first observed that individuals with high math anxiety performed similarly to those with low math anxiety on easy arithmetic problems but performed worse on more complex problems. One suggested explanation was that easy arithmetic problems, such as single-digit addition, is generally completed through retrieval, making minimal demands on WM resources. In contrast, more complex arithmetic problems, such as double-digit addition with a carry operation, generally requires one to complete the operations, making moderate to high demands on working memory resources. Math is generally considered to be a WM intensive domain, meaning that the burden on working memory resources imposed by math anxiety could account for some of the performance and achievement decrements we see in individuals with high math anxiety.

To date there is considerable evidence as to the importance of working memory in math performance and achievement [see Raghubar, Barnes, and Hecht (2010) for a recent review]. In general, working memory has been found to uniquely predict math performance above and beyond factors such as reading ability, processing speed, fluid intelligence (Raghubar et al., 2010). In addition, working memory ability has been found to be an important predictor of growth in mathematics skills overtime and it is common for children with math difficulties to have marked deficits in verbal and visuo-spatial working memory (LeFevre, DeStefano, Coleman, & Shanahan, 2005; Raghubar et al., 2010; Swanson & Jerman, 2006)().

It is hypothesized that working memory resources play a key role for less automatized and more complex mathematical computations (LeFevre et al., 2005). Sweller, et al. (1998) suggested that successful application of mathematical knowledge involves an intricate interplay between working and long-term memory. Early in learning, information has yet to be encoded into long-term memory, which leads to a high working memory burden as one attempts to consolidate the new content. With time and practice, that information is thought to become more automatized, becoming more readily available from long-term memory with minimal burden on WM resources. Supporting this view, Beilock et al. (2004) found that pressure (consisting of monetary, peer, and social evaluation components) was only detrimental for high-demand problems that were not frequently practiced. This suggests that for simple arithmetic, such as single-digit addition and multiplication, have usually been committed to long-term memory and the individual no longer needs to complete the calculation to reach the answer, leading to little reliance on working memory resources (see Ashcraft, 1995). In contrast, for more complex computations, such as two-digit addition with a carry operation, although the algorithm itself has been automatized, multiple pieces of information need to be held in mind to successfully complete the calculation, leading to a higher working memory load (for an in-depth discussion of mathematics and working memory see LeFevre et al., 2005).

Ashcraft and Krik (2001) completed the first study directly assessing the on-line effects of math anxiety on working memory capacity as a follow up to the Ashcraft & Faust (1994) and Faust et al. (1996) findings discussed previously. First, they found that individuals with high math anxiety had significantly lower working memory scores than those with low math anxiety for both word-based and computation-based WM tasks, but that higher math anxiety was more associated with lower computation-based working memory capacity than word-based working memory. Second, they explored whether math anxiety disrupts working memory during an on-line arithmetic task using a dual-task procedure. In the dual task condition, participants were first presented with a set of two to six letters to hold in mind, then asked to complete an arithmetic problem, and finally asked to recall the set of letters they were presented previously. Control tasks consisted of completing either the arithmetic task or letter memory tasks alone. In the dual-task condition, individuals with high math anxiety had a much higher error rate (~40%) when they had to keep six letters in mind while completing an arithmetic problem with a carry operation than in the single-task control condition (~15%). In addition, individuals with high math anxiety also had much higher error rates than individuals with medium or low math anxiety (~25%) in the dual-task condition. They also found similar findings in a third experiment using a counting like task instead of arithmetic. Ashcraft & Krik (2001) argue that these findings provide additional evidence to the account that math anxiety merely degrades math performance, the affective drop, and that math anxiety is not necessarily due to a deficit in basic numerical knowledge. However, Ashcraft & Krik (2001), do not provide any direct evidence as to the source of the working memory burden. Is it worries about math performance or something else that is burdening working memory resources?

More recently, Trezise and Reeve (2016) found that worry and working memory capacity have a reciprocal relationship. 14-year-old participants completed measures of working memory and math worry several times throughout the day as they prepared for a math test at the end of the day. Working memory was measured using an algebra-based operation span type task, to assess domain specific working memory. To assess worry, participants were presented with pairs of algebraic equations where they had to judge whether the value of a variable was the same in both equations, after each trial they reported how worried they felt during the previous judgement. At the end of the day, they completed an algebra test consisting of 16 linear algebra equations. They found that high intensity of worry predicted lower working memory capacity, and that lower working memory capacity predicted increases in worry. Most striking was their findings that individuals with initial low levels of worry and high working memory tended to maintain their levels of worry and working memory throughout the day and perform well on the final test, but individuals with initially intense worry and low working memory tended to have increasing worry and decreasing working memory capacity throughout the day and lower performance on the final test. These findings provide additional support as to the influence of anxiety on cognitive resources, and how the two could influence each other overtime.

Although these findings are very informative, they did not assess initial level of algebra performance and they used a very specific working memory task used that is likely susceptible to negative influence of math anxiety. If initial level of algebra skill was assessed, we would be able to have a clearer picture of how the reciprocal relationship between worry and math anxiety throughout the day changed performance. In addition, the very domain specific nature of the working memory task used does not allow us to know if worry influences working memory functioning in general or only working memory functioning in the context of math. Despite these drawbacks, Trezise & Reeve (2016) provide us with some of the first evidence as to the bidirectional relationship between math anxiety and working memory resources.

Such evidence on the continuous interplay between math anxiety and working memory could explain some of the fixed findings on the interaction between anxiety and working memory capacity on performance. Some studies have found that children with high working memory capacities seem to be more susceptible to the negative influence of math anxiety, likely due to their higher reliance on working memory intensive strategies in problem solving (Ramirez, Chang, Maloney, Levine, & Beilock, 2016; Ramirez et al., 2013; Vukovic et al., 2013). However, one study with adolescents showed a different pattern, that individuals with high trait anxiety and low working memory underperformed compared to those with high working memory (Owens, Stevenson, Hadwin, & Norgate, 2012). Similarly, Wang & Shah, (2013) found that for 3rd and 4th grade students solving mental arithmetic problems under pressure, children with low working memory performed worse that those with high working memory on more complex problems. It is possible that the one-time measure of anxiety and working memory in these studies lead to the divergent results between studies. As Trezise & Reeve (2016) demonstrated, working memory fluctuates throughout the day. Depending on whether the students were more or less anxious at the time of completing the working memory measures could have influenced their working memory scores. Differences between the samples in their initial anxiety and other factors could account for the divergent patterns in the findings. The two studies by Ramirez and colleagues focused specifically on math anxiety in young children (1st and 2nd grade). In contrast, Owens et al. (2012) assessed trait anxiety and not specifically math anxiety, used a composite score of cognitive performance based on a general math and a fluid intelligence measure, and their sample consisted of adolescents. While Wang & Shah (2013) didn't assess anxiety specifically but instead performance under a high-pressure context in a group of older children (3rd and 4th grade). Given the current evidence, it is difficult to conclude how working memory capacity specifically interacts with anxiety to influence math performance.

In summary, we know that working memory resources are important for math performance, that some evidence suggests that math anxiety leads to lower math performance through interference with working memory resources, and that there seems to be a bidirectional relationship between math anxiety and working memory. However, most of these data are correlational in nature; Ashcraft and Krik (2001) is still the only study, that I know of, that has directly assessed the on-line effects of math anxiety on working memory resources with Trezise & Reeve (2016) currently having done the only study exploring the bidirectional relationship between math related worry and working memory. Much more work is needed for us to have a clear understanding of how math anxiety and working memory interact to influence math performance.

Attentional Control Theory

More recently the processing efficiency theory has been updated to the attentional control theory. In processing efficiency theory, the main mechanism was conceptualized to be that the worry associated with anxiety leads to an increase in the occupation of cognitive resources, specifically working memory, needed for a task. The increased burden these cognitive resources leads to a decrease in task performance, especially for cognitively demanding tasks, by stealing resources that could and often should have been devoted to the task rather than to worries. In contrast, attentional control theory focuses on the influence of anxiety on attentional control. Eysenck et al. (2007, p. 339) state, “of central importance to the revised theory is the notion that anxiety decreases the influence of the goal-directed attentional system and increases the influence of the stimulus-driven attentional system.” The goal-directed attentional system being that which is devoted to controlling and executing the task at hand, while the stimulus-driven system is being driven by threatening stimuli, both internal (e.g. worries) and external (e.g. the presence of math problems).

In fact, some early evidence did suggest that math anxiety was associated with interference in attention control. Hopko, Ashcraft, Gute, Ruggiero, and Lewis (1998) explored performance on a reading task designed to measure inhibitory control towards distracting information and its relation to later memory performance. Participants were presented with ten, short non-math or twelve math related paragraphs to read in italicized font. Paragraphs included non-italicized distractor words that were either related to paragraph content, unrelated to the paragraph content, math words, or a string of Xs (control). Participants were instructed to read the italicized words out loud and ignore the distractor words. After each paragraph, participants completed four multiple-choice questions about the paragraph content. Overall, they found that individuals with low math anxiety completed the task in less time than those with medium or high math anxiety. In addition, there was a distractor by math anxiety interaction, such that all anxiety groups took similar time to read paragraphs with the x-string distractors but that individuals with medium or high math anxiety took significantly longer to read paragraphs with distractors that were either related or unrelated to the paragraph content. With regards to content memory, individuals in the math paragraph condition performed worse than those in the non-math condition but this was not influenced by individual level of math anxiety. Overall, these findings demonstrate that individuals with medium or high math anxiety may have a more challenging time ignoring distractors, or inhibiting attention to irrelevant information. Hopko et al. (1998) suggested that this failure to inhibit irrelevant information could account for the reduced working memory performance in individuals with high math anxiety. For example, if an individual is working on a word problem and fixates on irrelevant aspects of the problem, they are increasing the amount of information that they are attempting to maintain and manipulate in working memory. Worth noting is the fact that there were no differences in performance on the math versus non-math paragraphs for individuals with high math anxiety. This suggests that the difficulties to attentional control were not limited to math content or may not be based on math anxiety but instead based on more general anxiety which was not assessed.

More recently, much more evidence has come to light about difficulties in attentional control in individuals with high math anxiety. Individuals with high math anxiety have been found to take longer to respond to math-related than to neutral words in an emotional Stroop task, while math anxiety has been found to be unrelated to performance on the traditional color Stroop task (Hopko, McNeil, Gleason, & Rabalais, 2002; Suárez-Pellicioni et al., 2014; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2015). These findings suggest attentional difficulties that might specifically related to math-related contexts. Rubinsten, Eidlin, Wohl, and Akibli (2015) used a dot-probe task to explore attentional bias in individuals with math anxiety. Individuals with high math anxiety reacted more quickly when a probe was presented in the same location as a previously presented math prime than to neutral primes. Recent evidence has demonstrated that the effects of math anxiety on selective attention during numerical processing is context dependent. Ashkenazi (2018) had participants complete a numerical Stroop task in tandem with emotional priming. Before each Stroop trial, participants were presented with one of 30 prime words that were either negative (e.g. failure), neutral (e.g. notebook), or math words (e.g. division). In the numerical Stroop task, participants were presented with two numbers that varied in font size and value and were instructed to decide which was the numerically larger stimulus, while ignoring the previously presented prime. They found that individuals with high math anxiety were less accurate on trials with a math prime than on those with a neutral or negative prime. In contrast, individuals with low math anxiety performed similarly regardless of the primes presented. These findings suggest that when an individual's math anxiety is not previously primed they have little trouble processing simple magnitude judgements, however, when primed with math related words they are less likely to make accurate judgements. These results seem to be analogous to those found by Lyons & Beilock (2012) discussed earlier, that activation differences between math anxiety groups were most prominent during anticipation of doing a math task. Together, all these studies suggest that individuals with high math anxiety have trouble inhibiting irrelevant information, with some suggesting an attentional bias towards math related information (due to its threatening nature).

Although more evidence is appearing illustrating the relationship between math anxiety and attentional processes, there is still little literature on the topic. None of the studies discussed specifically explored how attentional processes in individuals with math anxiety could lead to lower math performance, nor did they assess general math performance. Studies that explicitly explore the relationship between attentional control, math anxiety, and math performance/achievement are needed for us to understand how attentional control fits into our understanding of the math anxiety and performance link. In addition, all the studies to date exploring attentional processes in individuals with math anxiety have been done in adults. We currently do not know if younger children or adolescents with math anxiety have the same attentional bias or lack of inhibitory control as adults.

Summary and Dissertation Aims

This far we know a fair bit about the behavioral, neural, and developmental correlates of math anxiety. As discussed previously, math anxiety is associated with lower math performance and achievement, decreased persistence in math related fields, increased avoidance of math, higher rates of negative attitudes towards math, and lower math self-efficacy and self-concept. We have begun to understand that even young children can have math anxiety, and that although genetic predisposition plays a role, that environmental factors seem to be most influential. Some of the environmental factors involved in the development of math anxiety and negative math attitudes are previous experiences with failure in math and teacher and/or parent attitudes towards math. We have also begun to understand that individuals with math anxiety tend to show different neural recruitment patterns than do individuals with low math anxiety, proving evidence for the physiological effects of math anxiety. Within the last two decades, researchers have begun exploring the possible mechanisms of math anxiety, and how it interferes with math performance. The two most common ideas are that 1) math anxiety acts as an additional cognitive burden on working memory resources, and 2) math anxiety leads to a dysfunctional attentional control system in math related contexts. So far, the evidence does suggest that math anxiety interferes with basic cognitive functions such as working memory and attentional control, which could account for the performance deficits often associated with math anxiety. However, the data is currently inconclusive on whether the interference with basic cognitive functions related to math anxiety is limited to math or more general.

An Unexplored Issue: Learning New Math, rather than Dealing with Already-Learned Material

Our understanding of math anxiety has grown by leaps and bounds in the last few decades, however, there are still many more questions left to be answered. The scope of this dissertation is to more closely examine how math anxiety interferes with the learning of new math information and the study strategies individuals with math anxiety tend to use.

Does math anxiety interfere with learning of novel math content? It is currently unclear. So far most of the research that has explored the math anxiety-performance link has only assessed the influence of math anxiety on previously existing knowledge or basic numerical processing skills. Previous studies have suggested that it is not necessarily that individuals with high math anxiety are less knowledgeable or less skilled in math but that their math anxiety leads them to perform less well on measures of math skill, the affective drop (Ashcraft & Moore, 2009). Although, some researchers do think that there is evidence that individuals with high math anxiety have some underlying deficit in low level numerical processing, it is unclear whether the effects of math anxiety on basic cognitive functions such as working memory and attentional control could account for such findings. Does that mean that individuals with high math anxiety learn new math information in the same manner as individuals with low math anxiety, and it is just their long-term performance in high pressure situations that is affected? We do not know. Some studies have assessed individuals with math anxiety's learning throughout an entire term. For example, Núñez-Peña et al. (2013) found that in a research methods course, students with high math anxiety had lower final grades than those with low math anxiety. However, these findings do not tell us much as to the extent to which math anxiety interfered with their day to day learning. All it tells us is that individuals with math anxiety tend to do worse throughout the term. This could have been due to several reasons; one possibility is it simply being the affective drop. To answer these questions, we need to closely examine the actual learning of novel math content. In addition, little research has explored the study strategies that individuals with high math anxiety use when learning math content. Do individuals with high math anxiety study new math information in a different manner than those with low math anxiety? These are questions that the current dissertation aims to answer.

The aims of the current dissertation are as follows:

1. To determine the extent to which math anxiety interferes with learning of new math content. In chapters 2 and 3, I will present results from a series of experimental studies in which I assessed math learning for individuals that vary in math anxiety and general math skill.
2. To determine if some study strategies lead to different learning outcomes based on individual differences in math anxiety and general math skill (Chapters 2 and 3).
3. To determine if individuals with high math anxiety use different study strategies that individuals with low math anxiety. In Chapter 4, I will present results from a survey assessing undergraduate students' study habits for quantitative courses and their math anxiety.

CHAPTER II

Math Anxiety, Math Skills, and Learning

As reviewed in Chapter I, it is hypothesized that the worry associated with math anxiety interferes with basic cognitive function in math related contexts (Ashcraft & Krik, 2001; Ashcraft & Moore, 2009; Chang & Beilock, 2016; Hopko et al., 1998; Suárez-Pellicioni et al., 2016). Two cognitive functions that have been the focus of research are working memory (the limited mental workspace used to store and manipulate information online; Miyake & Shah, 1999) and attentional control (the process of being able to attend to relevant information and inhibit attention to irrelevant information; Eysenck et al., 2007). Although math anxiety has often been shown to interfere with math performance (Ashcraft & Faust, 1994; Ashcraft & Krause, 2007; Faust et al, 1996; Hembree, 1990; Xin Ma, 1999; Maloney et al., 2010; Ramirez et al., 2013), to date, there are no studies specifically assessing the influence of math anxiety on learning of novel math content. Some research has shown that math anxiety is associated with deficits in basic numerical cognition (e.g. magnitude comparisons; Maloney et al, 2010; Maloney et al., 2011), however, it is unclear if these defects are merely a reflection of math anxiety interfering with basic cognitive functions. In contrast, some suggest that it is not that individuals with math anxiety have lower math skills per se, but that math anxiety itself depresses math performance by interfering with basic cognitive processes (Ashcraft & Faust, 1994; Ashcraft & Krik, 2001; Ashcraft & Moore, 2009; Faust et al. 1996). If math anxiety indeed merely depresses math performance, this would suggest that math anxious individuals' mathematical knowledge is relatively intact. However, since all previous studies have only examined the effects of math anxiety on preexisting knowledge it is impossible to know if math anxiety interferes with the acquisition of new mathematical knowledge.

The primary objective of the current study is to assess how individual differences in math anxiety influence learning of new mathematical content. We need to understand the effects of math anxiety on the acquisition of new math knowledge to develop strategies for combating its negative short- and long-term effects (e.g. lower achievement and avoidance of future math courses, respectively). If math anxiety does not interfere with the acquisition of new information, we would know that we need to focus on strategies that alleviate the depressive effect of math anxiety on performance. On the other hand, if students with high math anxiety are not mastering new math material, we would need to focus on strategies that help students both master the material and alleviate the negative performance effects of math anxiety. With the current evidence it is impossible to know whether individuals with high math anxiety experience difficulties mastering novel math content.

Learning new material is generally cognitively demanding, but some learning strategies are thought to burden cognitive resources less than others, possibly making them more conducive to learning for individuals who already have constraints on their cognitive resources, such as those with math anxiety. The secondary objective of the current study is to assess if different learning strategies interact with individual differences in math anxiety and general math skill to influence learning outcomes.

Math Learning and Basic Cognitive Processes

The nature of the learning task itself influences the extent to which cognitive processes are recruited and which cognitive processes are crucial to success. Generally, tasks that are complex place more stress on cognitive processes than do simple ones. Let us compare simple single-digit addition to double-digit addition with a carry operation. Most of us can complete single-digit addition quickly from memory, we do not need to calculate 2+2 to get to the answer 4. In contrast, if we were to add 24+59, most would need to complete the calculation, which includes a carry operation. The latter example is much more working memory demanding and requires more attentional control for successful completion. Most are not simply retrieving a single fact from memory, but they need to maintain multiple pieces of information in mind at once. The same general principle would apply to learning new math information, such that learning new information is more cognitively demanding than retrieving previously existing knowledge (Sweller et al., 1998). In addition, the manner with which one learns, or studies, new math information can further stress cognitive resources. However, it is currently unclear whether cognitively demanding study strategies benefit or hinder learning of new math content, especially for individuals who might already have strained cognitive resources.

According to Sweller and colleagues (1998), cognitive load should be minimized during learning, to avoid taxing cognitive resources which facilitate learning. One recommended strategy that minimizes cognitive load is worked examples (Sweller et al., 1998). Worked examples are example problems that are presented with a step-by-step breakdown that is used for study. Theoretically, worked examples are thought to reduce cognitive load because one does not need to try and remember all the relevant information, and the individual need only to study the example. Worked examples have been shown to benefit learning in domains such as math, computer science, and engineering (Cooper & Sweller, 1987; Sweller, Chandler, Tierney, & Cooper, 1990; Sweller & Cooper, 1985; Tuovinen & Sweller, 1999). Sweller & Cooper (1985) studied the effectiveness of using worked examples over traditional problem solving for study in Algebra. Ninth grade students were presented with two examples of problems they would be solving. Participants were then presented with eight study problems. Half the participants were instructed to solve all eight problems (active problem-solving group), and the other half were instructed to study four worked examples interleaved with four practice problems (worked example group). Those in the worked example group solved the test problems faster than those in the active problem-solving group. These findings suggest that studying worked examples leads to more efficient performance when interleaved with practice problems than solving practice problems alone. However, there were no overall differences in accuracy between the two groups. Subsequent evidence suggests that the benefit for studying worked examples is more pronounced under certain circumstances. For instance, some studies have found an interaction between worked examples and individual expertise (Cooper & Sweller, 1987; Kalyuga, Chandler, Tuovinen, & Sweller, 2001; Tuovinen & Sweller, 1999), such that worked examples were more beneficial for individuals with low previous knowledge (based on their math performance from the previous school year). It is possible that the use of worked example could also have differential effects on performance based on other individual differences, such as math anxiety.

Although reducing cognitive load during learning may improve performance for some, it is still not clear if it would benefit learning of novel math information for individuals with high math anxiety. The studies discussed above were based on previously existing knowledge, and not necessarily a novel topic. In Sweller & Cooper (1985), students were already taking Algebra and were currently learning in class how to solve different types of problems. In the study, participants were merely presented with types of problems that they did not necessarily have experience with before, but they already had all the relevant knowledge available to be able to solve the problem if asked to do so without any instruction. All worked examples seemed to help participants do is be able to know how to approach specific types of problems more quickly than those who completed only practice problems. In contrast to idea that reducing cognitive burden of the learning activity is beneficial for learning, some evidence suggests that more effortful learning strategies lead to better learning and long-term retention.

The education and memory literature has long provided support for constructivist learning approaches, in which learning is thought to occur best when students are actively constructing their own knowledge instead of being passive receivers of information, despite it being more cognitively demanding (Bertsch, Pesta, Wiscott, & McDaniel, 2007; DeCaro & Rittle-Johnson, 2012; Hmelo-Silver, Duncan, & Chinn, 2007; Rittle-Johnson & Kmicikewycz, 2008; Slamecka & Graf, 1978; Wheatley, 1991). One example is the generation effect, a phenomenon in which information that is generated is better remembered than information that is passively read (Slamecka & Graf, 1978). Bertsch and colleagues (2007) found generation to benefit recall by almost a half of a standard deviation (0.40). They also found that the generation effect increased with increasing retention intervals and was more beneficial for difficult material, likely because generation helps curb the normal rate of forgetting that generally occurs when simply reading materials.

The vast majority of studies have explored the generation effect in verbal recall. However there have been several studies illustrating that the benefit of generation during study extends to math material as well. McNamara & Healy (1995, 2000) presented initial evidence as to the benefit of generation during study of multiplication problems but not for addition. Actively practicing multiplication problems was more beneficial for later test performance than was using calculators. Pyke and colleagues (2008) found a benefit of generation for repeated but not novel alphabet arithmetic problems. Rittle-Johnson & Kmicikewycz (2008) further explored whether the generation effect would also apply to novel multiplication problems. Thirty-seven third grade children with average math abilities were assigned to either study by completing 12 multiplication problems manually (generation) or to use a calculator. The following day participants were given a posttest, and two weeks later a retention test. No calculator use was allowed on the posttest or the retention test. Rittle-Johnson & Kimicikewycz (2008) found that students with low previous knowledge (based on pre-test performance) in the generate condition benefited more than those who used a calculator during study. However, those with high previous knowledge performed similarly well in both conditions. This study suggests that actively practicing math material during study might be especially important for students with low previous knowledge.

In summary, active construction of to-be-learned information has been shown to enhance performance for math material. However, I speculate that generation is generally only beneficial when active construction of the novel information is successful. If the material is too complex and inherently requires more cognitive resources, successful generation of the material might be less likely. This could account for the seemingly at odds findings that both worked examples and active practice during study benefits individuals with low prior knowledge. The studies that support the use of worked examples used algebra as their content, while the studies that support the use of active practice only used addition or multiplication. Algebra is inherently a more cognitively demanding content area than is multiplication and addition since it generally involves retrieving and organizing more pieces of information, steps, and rules. It is possible that generation during study is beneficial when the material is relatively low in cognitive demand, but the use of worked examples is more effective for more cognitively demanding materials, especially for individuals with low prior knowledge. In addition, the distinction between low and high knowledge groups were made differently in the studies that assessed worked examples versus those that assessed generation. The worked example study used past class performance as their knowledge criteria while the generation study used pre-test performance. Class performance is determined by a variety of factors, including homework completion and exam performance and is not a direct measure of student's content knowledge compared to a topic specific pre-test. These differences in the definition of low versus high knowledge groups could also account for the conflicting evidence on the benefits of worked examples versus generation. There are relatively few studies in both areas, and no studies to my knowledge have assessed how other characteristics, such as math anxiety, might interact with the different study strategies to influence learning outcomes.

The Current Studies

The existing research illustrates some of the ways math anxiety interferes with performance but does not provide evidence as to the effects of math anxiety on learning of new math content. In addition, it is unclear what study strategies lead to superior math performance and as to whether such strategies differ with regards to learning outcomes for new material. Some studies suggest that active practice leads to better outcomes while others suggest that studying worked examples is superior. It is also suggested that individual differences in previous knowledge might influence the effectiveness of the study strategy, but the role of math anxiety in this relationship is still unknown. The current study seeks to fill some of these holes in our existing understanding of math anxiety and its relationship with learning of new math content and the effectiveness of different study strategies for individuals who vary in math anxiety and general math skill.

The objectives of the current studies are as follows:

1. To determine the influence of math anxiety on learning of new procedural math content, above and beyond general math skill.
2. To determine the efficacy of worked examples versus active problem solving as study strategies for individuals that differ in math anxiety and math skill.
3. To determine if there are differences in learning confidence based on individual's math anxiety and study strategies use.

Mathematical knowledge is thought to consist of both conceptual and procedural components (Rittle-Johnson, 2017). The current study specifically focuses on the acquisition of new procedural knowledge, the knowledge of the steps needed to complete a task and the ability to carry them out successfully. In both study 1 and 2, mostly naïve participants were taught to perform base number conversions, the procedure involved in converting a number in base 10 into an alternate base. After being introduced to the topic with a brief video lesson, half of the participants studied the procedure using worked examples interleaved with practice problems, while the other half studied only by completing practice problems. Participants then took a five-minute break before completing an immediate test in study 1 or returned for a delayed test one-week later in study 2. All participants completed measures of math anxiety and general math skills.

Study 1 Methods

Participants

214 University of Michigan undergraduate students participated either for credit or for $20. 16 people did not return for session 2, and 4 were not administered the math skills measure. 194 students had complete data for math anxiety, math skill, and the learning task. Participants were told multiple times that they must have not learned base number conversions in the past to

be eligible for participation. Still of the 194, only 170 had confirmed that they never learned base number conversions before. It is unclear whether the remaining participants had learned base number conversions before, considering the number of times they were notified of the eligibility requirements throughout the study. There were no significant differences in performance between those who had learned base number conversions previously and those who were novices, which may suggest that even though some had learned base number conversions before they might not have remembered the procedure. Since those who reported having learned base number conversions previously did not differ from their novice counterparts in their performance, this suggests that they may have been relearning the procedure and did not currently have fluency, qualifying them to be included in the analyses. However, all main analyses were run both with and without those who claimed to have learned base number conversions previously. Of the 194, 36.1% (N = 70) were male with the average age of 20.54 years (SE = 0.32). 44.8% of the sample were in their first year of college, 27.8% in their second, and the remaining 27.3% were further along. 99 and 95 individuals were randomly assigned to the worked example and active problem-solving groups respectively. 67% of the sample completed either calculus 1 or higher, 15.5% completed pre-calculus or lower, and 17.5% reported their last course was statistics. Of those with the top third of math anxiety scores, 64.06% had completed calculus 1 or higher, 18.75% had completed pre-calculus or lower, and 17.19% had completed statistics as their most recent quantitative course. Of those who completed calculus 1 or higher 31.5% had math anxiety scores in the top third. 29.9% of the sample had a social science major, 27.5% were a science, technology, engineering, or mathematics major, 17.5% were in business, economics, or finance, and 24.7% were humanities, arts, or undecided majors.

Design

The current study is a two-session study with sessions taking place between two to seven days apart. The total sample consists of two sub-samples who underwent slightly different protocols, which will be referred to as sample 1 (N = 64) and 2 (N =130). All participants were required to participate in two sessions. Upon arrival participants were randomly assigned to either the worked example (WE) or active problem-solving (APS) group. The first session consisted of pre-learning and post-learning metacognitive questionnaires, base number conversions lesson and study sessions, and an immediate base number conversion test. During the second session individuals completed a delayed base number conversion test (only sample 1 participants), delayed metacognitive questionnaire and an individual differences battery. After collecting data from sample 1, we decided to shorten the protocol on day 2 and cut out the delayed test since there was no evidence of performance change from the immediate to the delayed test. In addition, cutting the delayed test allowed us to be able to run more participants in a shorter period. Individuals in sample 1 completed the second session five to seven days after the first session. Since sample 2 did not complete a delayed test, they completed their second session two to seven days after the first session.

Materials

Base number conversion task. In Eprime 2.0, participants were presented with the initial lesson on base number conversions, completed practice trials, and the base number conversion immediate test (as well as the delayed test for sample 1). The base number conversion task took approximately 40 minutes of session 1 and 10 minutes of session 2 for sample 1 participants. The base number conversion lesson was a brief 10-minute YouTube lesson on calculating base number conversions using the remainder method (see link for original video here https://www.youtube.com/watch?v=TjvexIVV_gI). The lesson consisted of the instructor first explaining the base 10 nature of Arabic numerals, e.g. that we use 0 through 9 to represent the numbers and add additional places, such as tens or hundredth place, to represent larger numbers. The instructor then generalized the explanation to other number systems and works through several examples of converting numbers in base 10 into an alternate base (e.g. base 2). All participants were presented with a print out with step by step details of the remainder procedure to refer to during the video and add notes to.

After participants watched the video, they were presented with a set of six practice problems. If subjects had been assigned to the WE group, participants from sample 1 were instructed to study three example problems and solve three problems (alternating; example, practice problem, example, etc.) and participants from sample 2 studied four examples and solved two practice problems (example, example, practice, example, practice). Procedures were altered during the collection of the data to attempt to maximize differences between the worked example and active problem-solving procedures. I really wanted to get a better idea of whether studying examples influenced learning rather than the practicing of the procedure, and therefore decided to reduce the number of practice problems for the worked example group. Participants assigned to APS were presented with six problems (practice problem, practice problem, practice problem, etc.), in both sub-samples. Practice problems required participants to convert numbers from base 10 into base 2. See Appendix 1 for all practice problems presented. Practice problems were counterbalanced with half of the participants presented with order A and the other half with order B in Appendix 1. Participants had a maximum of ten minutes to solve or study each problem/example presented.

Once all six practice/example problems were presented participants were given a five-minute break during which they were to complete a bird word search. After the five-minute break, the computer presented instructions for the immediate base number conversion test. The test consisted of eight new base number conversion problems, converting numbers in base 10 to either base *5, 6, 7, or 8*. See Appendix 1 for base number conversion test problems. Tests were counterbalanced for individuals in sample 1, with half of the subjects receiving Test A for session 1 and Test B for session 2 while the rest received the tests in the reverse order. All participants from sample two received Test A. Participants were given a maximum of two minutes for each problem.

Metacognitive questionnaires. The metacognitive questionnaire consisted of a series of questions assessing the individual's confidence in learning base number conversions and their predictions of how many problems he/she would successfully solve. Participants were prompted to give confidence ratings before the base number conversion lesson, after the immediate base number conversion test, and again at the beginning of session 2. Before the base number conversion lesson, participants were instructed to use a scale of 0 to 100, with 0 being "not at all confident" and 100 being "completely confident", to rate how confident he/she is in his/her ability to learn a new mathematical computation and his/her ability to remember how to calculate the new mathematical computation in one week. After the immediate base number conversion test, participants used the same scale to rate their confidence in their learning of the new material and their ability to complete the computation in one week. In addition, participants guessed how many of the eight problems they got correct on the immediate test and to predict how many of eight new problems they would get correct in one week. For participants from sample 1, they again rated their confidence in learning the material and their ability to remember the computation and guessed how many problems they got correct for the immediate test, delayed test, and a test in one week after the delayed test during session 2. Session 2 confidence prediction was not analyzed because of the potential effects of the variable retention interval (between two days and one week).

Individual Differences Battery.

Math anxiety. The abbreviated Mathematics Anxiety Scale (AMAS) is a shortened nine-item math anxiety questionnaire adapted by Hopko et al. (2003) from the original 98 item Mathematics Anxiety Scale by Richardson & Suinn (1972). Participants were instructed use a scale of 1 (not anxious at all) to 5 (very much anxious) to rate how anxious a given situation made them feel. For example, "Taking an examination in a math course."

Working memory. We included a measure of working memory to make sure that our two conditions were made up of participants with equivalent cognitive profiles. We opted to use the computerized symmetry span task, a well validated and reliable measure of visuo-spatial working memory task. Participants are presented with a 4x4 matrix, of which various sectors are highlighted one at a time. Participants are to memorize which sectors of the matrix were highlighted as well as the order in which they were presented. As they are holding the matrix pattern in mind, they are presented with an additional static pattern for which they are to judge symmetry. The task begins with highlighting three sections of the matrix and becomes increasingly difficult till the individual makes a pre-specified number of mistakes, which indicates WM capacity is reached (see Redick et al., 2012). The task took approximately 15 minutes to complete but completion time varied by individual.

Math skill. The wide range of achievements test (WRAT) 4 Math computation subtest consists of 40 basic mathematics questions (ranging from addition to algebra) ordered by difficulty. The WRAT is a normed, reliable, and validated measure of general math skill (see Wilkinson & Robertson, 2006). Individuals are read the instructions from the WRAT packet by the researcher and given 15 minutes to complete as many problems as possible. If they completed all 40 problems before the 15 minutes is up they were asked to check their work. All analyses used the number correct out of 40 as the WRAT score.

Measures not relevant to research questions. Participants also completed additional questionnaires that will not be assessed in this study and will be explored in future papers, the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich et al., 1991), Need for Cognition (Cacioppo & Petty, 1982), and Theory of Intelligence scales (Dweck, 2013).

Procedure

Upon arriving, participants read and signed the consent form, explaining in general terms their role in the study. After giving written consent, participants were led into the experiment room that contained the stimulus computer. First, participants completed the pre-task questionnaire using the Qualtrics platform, which consisted of the math anxiety scale as well as the initial set of metacognitive questions. After completing the initial questions, the base number conversion task was started in Eprime. The first screen informed participants that to be eligible, subjects must have not previously learned about base number conversions, and if they have, to notify the researcher right away. As mentioned earlier, despite this warning, many participants continued with the study even though they reported that they had learned base number conversions in the past. The task then proceeded as described above. After the lesson and practice trials, participants took a five-minute break, followed by the immediate test. Participants then completed the post-task metacognitive questionnaire on Qualtrics. Participants were then thanked for their participation and handed an appointment slip with the date and time of their session 2. Two to seven days after session 1, participants returned to complete the delayed test (sample 1 participants) and the individual differences battery. After all measures were completed, participants were thanked for their time and given a debriefing sheet that explained the study aims and provided some references.

Study 1 Results

All t-tests reported are Welch's t-test for unequal variance unless otherwise reported

Group Differences and Descriptives

There were no significant differences between sample 1 and sample 2 participants on immediate test number correct, problem completion time, and confidence predictions, so both samples were combined for all following analyses. There were no significant differences between individuals in the worked example and active problem-solving group in age, gender, math anxiety, and math skill scores. However, the active problem-solving group had significantly higher visuo-spatial working memory scores (M = 30.89, SE = 0.80) than did the worked example group (M = 28.22, SE = 0.84), $t(183.8) = -2.30$, $p < 0.05$. For overall and group descriptive statistics see Table 1.1. Women had significantly higher math anxiety scores $t(149.71) = -2.57$, $p < 0.05$ and lower math skill (WRAT) scores $t(154.15) = 2.22$, $p < 0.05$ than men, see Table 1.2 for means and standard errors. However, gender differences in math anxiety might be due to increased willingness of women to report anxiety than men. Since gender was confounded with math anxiety, gender was not included as a covariate in the main analyses. Scores on the immediate base number conversion test were skewed left with 39.2% of the sample receiving the perfect score of 8 correct, 19.6% receiving 7, 14.9% with 6, and the remaining 26.3% receiving scores of 5 or less. Due to the non-normal distribution of scores on the immediate test, analyses were conducted using both linear and logistic regression. In a classroom context, a score below 60% would be considered failing, due to the real world meaning of this, we decided to consider scores greater than 5 as passing and scores less than 5 as failing in the logistic regression.

Table 1.1 Means and Standard Errors by Condition

Measure	Overall *M*(*SE*)	Worked Example *M*(*SE*)	Active Problem-Solving *M*(*SE*)
Immediate Test (# Correct)	5.95 (0.19)	5.85 (0.27)	6.05 (0.27)
Immediate Test Problem Completion Time (seconds)	49.44 (1.68)	48.73 (2.56) [*N* = 94]	50.14 (2.20) [*N* = 95]
Pre-Task Math Anxiety Sum	24.84 (0.49)	25.11 (0.73)	24.55 (0.66)
Math Skill (WRAT # Correct)	34.49 (0.28)	34.52 (0.39)	34.47 (0.41)
Visuo-Spatial Working Memory (SSPAN Partial Load Score)	29.54 (0.59)	28.22 (0.84) [*N* = 94]	30.89 (0.80) [*N* = 92]
Pre-Task Learning Confidence	65.11 (1.56)	64.08 (2.31)	66.19 (2.11)
Post-Task Learning Confidence	70.75 (2.14)	73.46 (2.89) [*N* = 96]	67.90 (3.16) [*N* = 91]
Pre-Task Memory Confidence	53.14 (1.68)	51.81 (2.58)	54.53 (2.14)
Post-Task Memory Confidence	63.73 (2.10)	64.73 (3.00) [*N* = 96]	62.68 (2.95) [*N* = 91]

Table 1.2 Means and Standard Errors by Gender

Variable	Male *N* = 70 *M*(*SE*)	Female *N* = 124 *M*(*SE*)
Pre-Task Math Anxiety	23.20 (0.78)	25.76 (0.62)
Math Skill	35.23 (0.45)	34.08 (0.36)

Base Number Conversion Learning

Number correct. To explore whether study condition, math anxiety, or math skill influence learning outcomes, I first ran a linear regression. The model consisted of study condition (worked example or active problem solving), math anxiety (pre-task), math skill

(WRAT number correct), math anxiety X math skill, study condition X math anxiety, study condition X math skill, and study condition X math anxiety X math skill interactions as predictors of performance on the immediate base number conversion test. Sub-sample was used as a covariate for all analyses. The full model significantly predicted performance F (8,185) = 4.14, $p < 0.001$, $r^2 = 0.15$ (See Table 1.3 for all values). Math anxiety was a marginally significant predictor, β = -0.13, t(185) = -1.82, $p = 0.07$, with higher math anxiety scores associated with worse performance on the immediate test. Math skill was a significant predictor of immediate test performance, β = 0.29, t(185) = 4.18, $p < 0.001$, with higher math skill associated with better performance on the immediate test. Study condition was not a significant predictor of test performance, and neither were any of the interactions. When including only those who reported never having learned base number conversion $N = 169$, the results are similar. The full model is significant F(8,161) = 4.33, $p < 0.001$, $r^2 = 0.18$. Math anxiety and math skill are both significant predictors of base number conversion performance, β = -0.23, t(161) = -3.05, $p < 0.01$ and β = 0.27, t(161) = -3.63, $p < 0.001$ but none of the interactions were significant. Exploring the p-p plot in both analyses shows that the residuals were not normally distributed.

Table 1.3 Linear Regression Values Predicting Base Number Conversion Immediate Test Performance

Source	*B*	*SE B*	Β	*t*	*P*
Sample	-0.64	0.39	-0.12	-1.67	0.10
Study Condition	-0.21	0.36	-0.04	-0.58	0.56
Math Anxiety	-0.05	0.03	-0.13	-1.82	0.07+
Math Skill	0.19	0.05	0.29	4.18	0.00***
ConditionXMath Anxiety	-0.05	0.05	-0.06	-0.88	0.38
ConditionXMath Skill	0.10	0.09	0.07	1.05	0.30
Math SkillXMath Anxiety	-0.01	0.01	-0.09	-1.28	0.20
CondXMathSkillXAnxiety	-0.00	0.01	-0.01	-0.12	0.91

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Due to the bimodal distribution of the scores of the immediate test and non-normality of the residuals in the linear regression, we also analyzed the data using logistic regression. Immediate test scores were first converted into a bimodal variable, scores from 0-5 were considered failing and assigned a 0 (26.3%), and scores greater than 5 were assigned a 1 (73.7%). The model used the same predictors as the linear regression. The full model was a significant predictor of passing the immediate test, χ^2 (8) = 32.42, $p < 0.001$, Cox & Snell R^2 = 0.15 (see Table 1.4 for all values). Math anxiety and math skill were significant predictors of passing the immediate test, Exp(B) = 0.89, $p < 0.01$, 95% CI [0.83,0.97] and Exp(B) = 1.29, $p = 0.001$, 95% CI [1.12,1.48] respectively. Each unit increase in math anxiety score is associated with a decrease in likelihood of passing the immediate test (see Figure 1.1), and each unit increase in math skill leads to an increase in the likelihood of passing the immediate test (see Figure 1.2). In addition, study group X math skill interaction was marginally significant, Exp(B) = 0.84, $p = 0.07$, 95% CI [0.70, 1.01], with individuals with low math skill in the worked example group being less likely to pass than high skill individuals and low skill individuals in the active problem-solving group (see Figure 1.2). Study condition and the remaining interactions were not significant predictors of passing the immediate base number conversion test. Again, when restricting the analysis only to those who reported having never learned base number conversions the results were similar. The full model was significant, χ^2 (8) = 31.19, $p < 0.001$, Cox & Snell R^2 = 0.17. Math anxiety and math skill were significant predictors of passing the immediate test, Exp(B) = 0.88, $p < 0.01$, 95% CI [0.81,0.96] and Exp(B) = 1.29, $p = 0.001$, 95% CI [1.10,1.50] respectively. In addition, study group X math skill interaction was marginally significant, Exp(B) = 0.83, $p = 0.07$, 95% CI [0.68, 1.01].

Table 1.4 Logistic Regression Values Predicting Base Number Conversion Immediate Test Performance

Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B*)
Sample	0.52	0.37	1.93	0.17	1.68	[0.81, 3.50]
Study Condition	0.18	0.39	0.21	0.65	1.20	[0.55, 2.59]
Math Anxiety	-0.11	0.04	8.11	0.004	0.89	[0.83, 0.97] **
Math Skill	0.25	0.07	11.95	0.001	1.29	[1.12, 1.48] ***
ConditionXMath Anxiety	0.06	0.06	0.98	0.32	1.06	[0.95, 1.19]
ConditionXMath Skill	-0.18	0.10	3.31	0.07	0.84	[0.70, 1.02] +
Math SkillXMath Anxiety	-0.02	0.01	2.61	0.11	0.98	[0.97, 1.00]
CondXMathSkillXAnxiety	0.01	0.01	0.44	0.51	1.01	[0.98, 1.03]

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Figure 1.1 Probability of Passing Base Number Conversion Test by Math Anxiety and Group

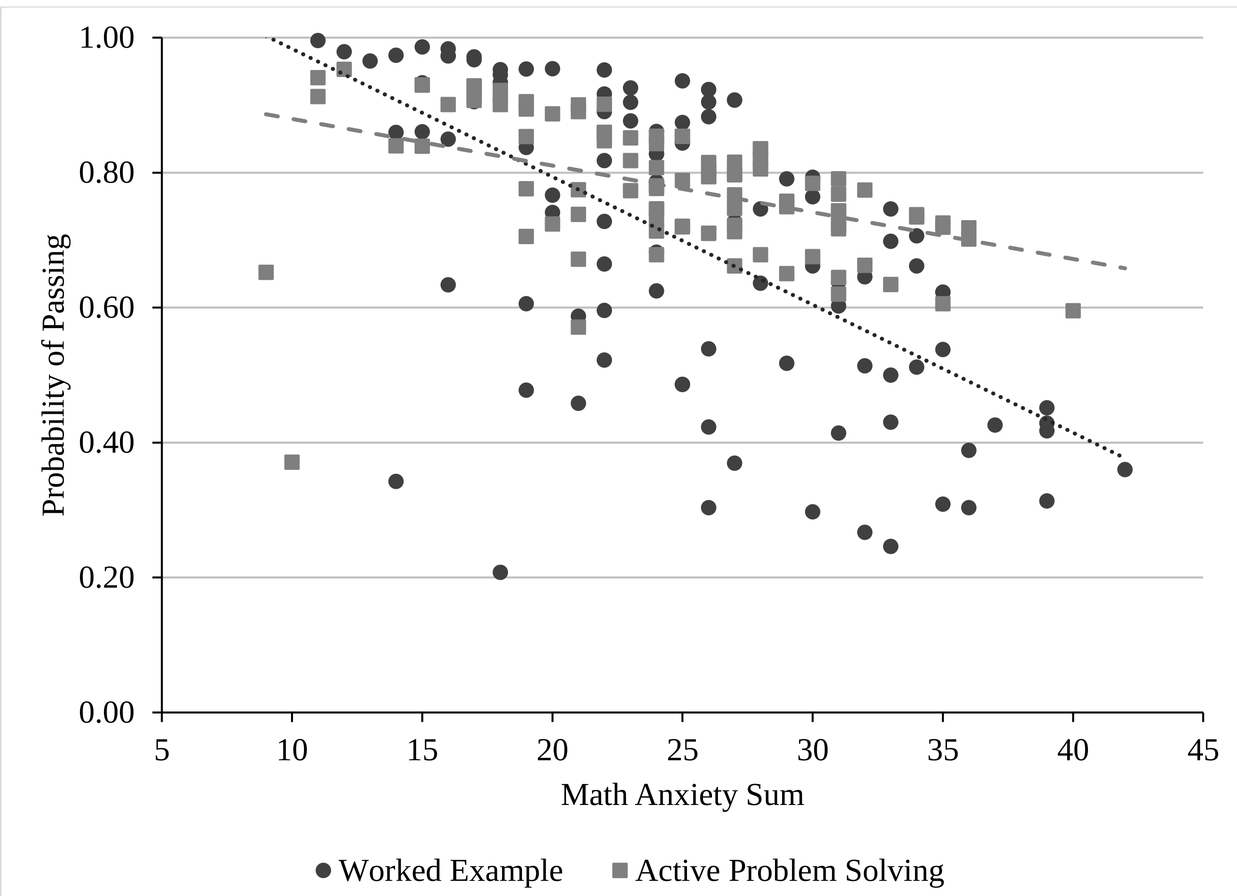
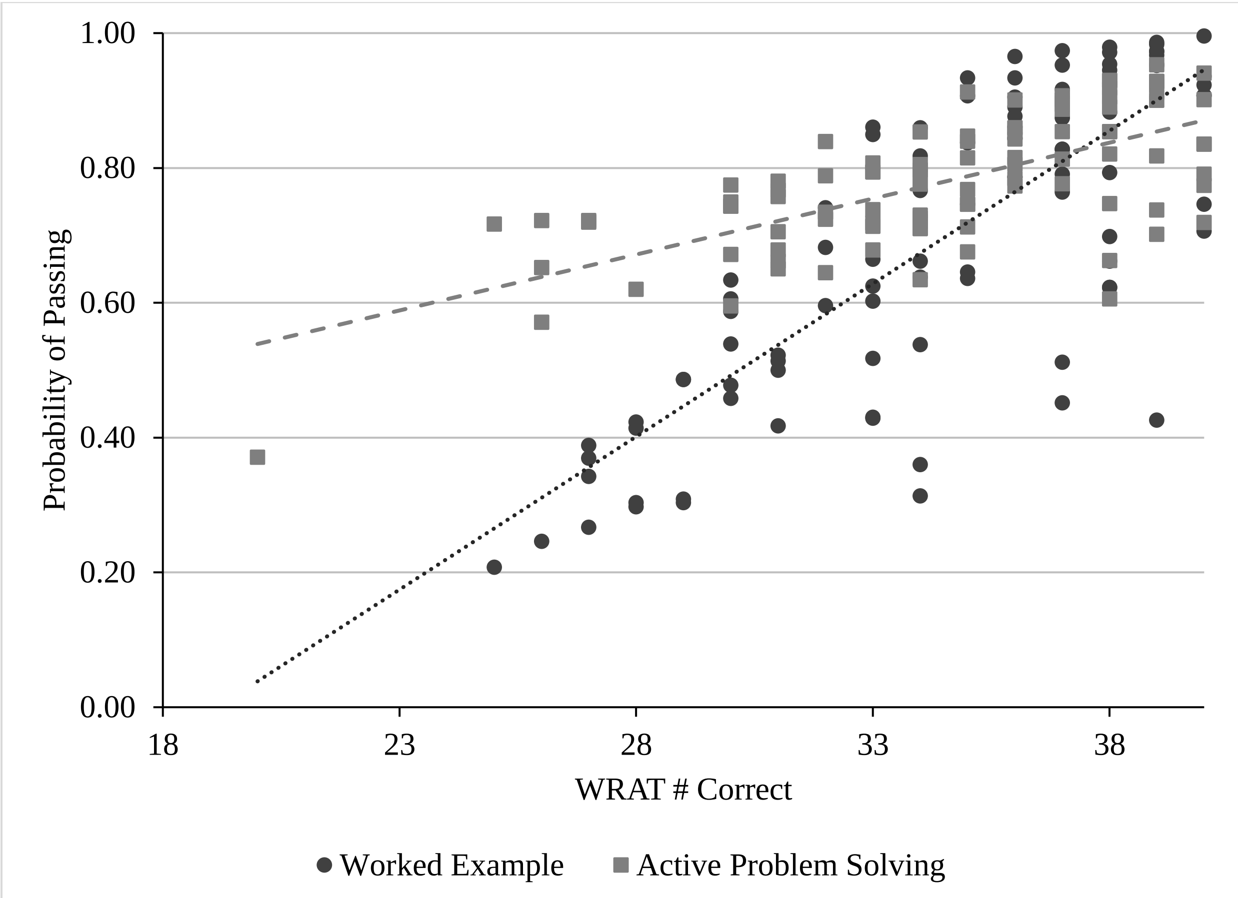


Figure 1.2 Probability of Passing Base Number Conversion Test by Math Skill and Group



Problem Completion Time. A linear regression with sample, group, math anxiety, math skill, and all interactions as predictors was used to predict problem completion time on the immediate base number conversion test. There were only completion time data for 187 or the 194 individuals due to loss of the computer files. The full model was a significant predictor of problem completion time, $F(8,180) = 4.99$, $p < 0.001$, $r^2 = 0.18$. Math skill (WRAT sum score) was the only significant individual predictor of completion time $\beta = -0.36$, $t(180) = -5.21$, $p < 0.001$, with increasing math skill score associated with decreased problem completion time. Neither study group, math anxiety, were significant predictors of problem completion time. There were no significant interactions.

Learning and Memory Confidence

To determine if study group, math anxiety, or math skill are related to changes in learning and memory confidence scores, we calculated a difference score between pre-task and post-task metacognitive measures from session 1 to use as the dependent measure. Only 187 individuals had both pre-task and post-task metacognitive measures completed from session 1. The full model included the same predictors as those used in previous linear regressions with the addition of pre-task metacognitive scores as a covariate. Two separate models were run one with learning confidence difference score and memory confidence difference scores as the dependent variables. For learning confidence, the full model was a significant predictor of learning confidence change from pre to post base number task, $F(9,177) = 4.42$, $p < 0.001$, $r^2 = 0.18$. Pre-task learning confidence significantly predicted learning confidence change, β = 0.34, $t(177) = 4.15$, $p < 0.001$. Higher pre-task learning confidence was associated with a greater decrease in learning confidence from pre-task to post-task in session 1. In addition, study condition was a significant predictor of learning confidence change, β = -0.16, $t(177) = -2.29$, $p < 0.05$, with the worked example group having a greater increase from pre-task to post-task learning confidence scores than the active problem solving group (see Figure 1.3). Math skill score was also a significant predictor of learning confidence change, β = -0.32, $t(177) = -4.30$, $p < 0.001$, with higher math skills scores associated with an increase in learning confidence from pre-task to post-task during session 1 (see Figure 1.4). No other variables were significant predictors and there were no significant interactions.

For memory confidence, the full model was a significant predictor of change in memory confidence from pre-task to post-task, $F(9,177) = 6.24$, $p < 0.001$, $r^2 = 0.24$. Pre-task memory confidence significantly predicted memory confidence change, β = 0.41, $t(177) = 5.58$, $p < 0.001$. Higher pre-task memory confidence was associated with a greater decrease in memory confidence from pre-task to post-task in session 1. In addition, math skill was a significant predictor of memory confidence change, $\beta = -0.34$, $t\ (177) = -5.00$, $p < 0.001$, with greater math skill associated with greater increase in memory confidence score from pre-task to post-task. No other variables were significant predictors, and there were no significant interactions.

Figure 1.3 Learning Confidence Change from Pre to Post-task by Group

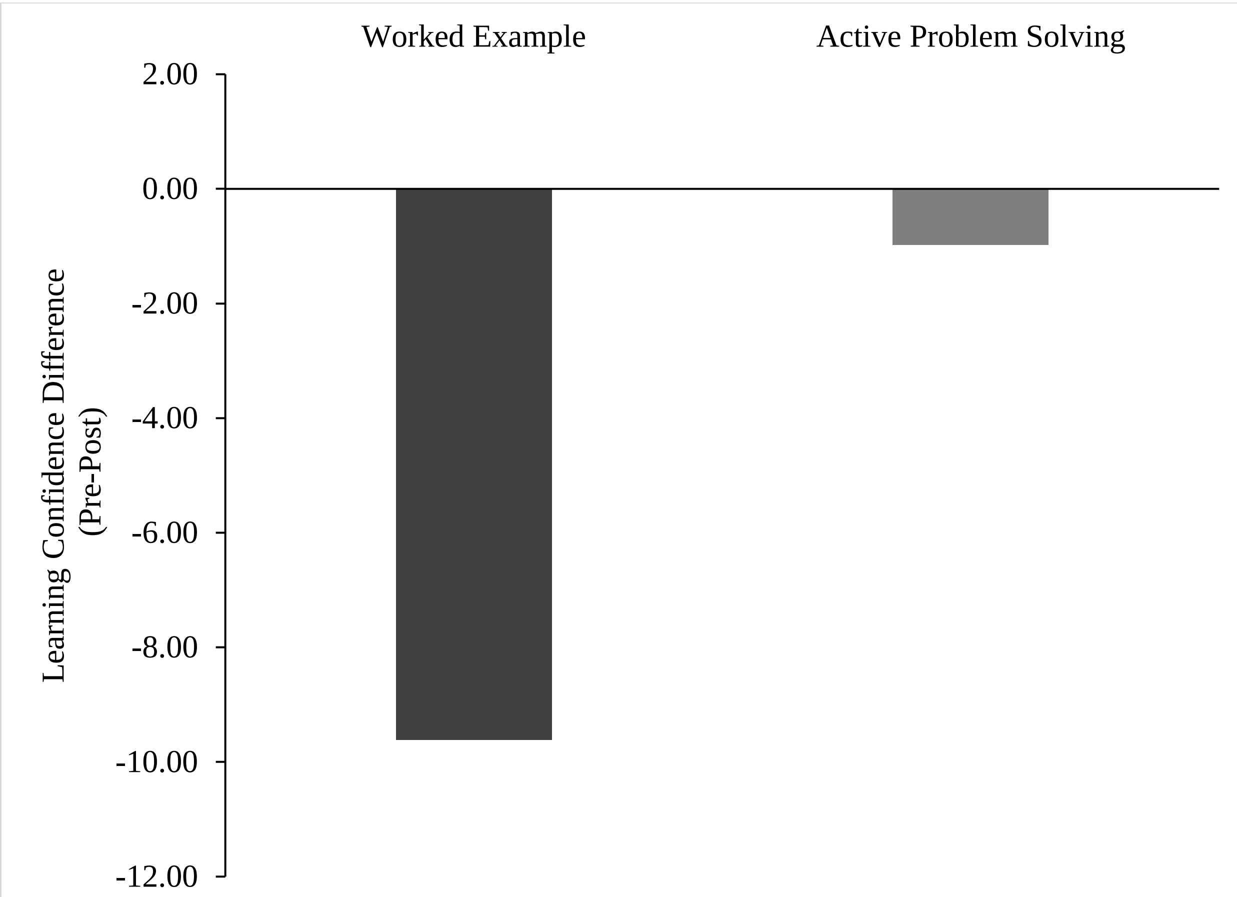
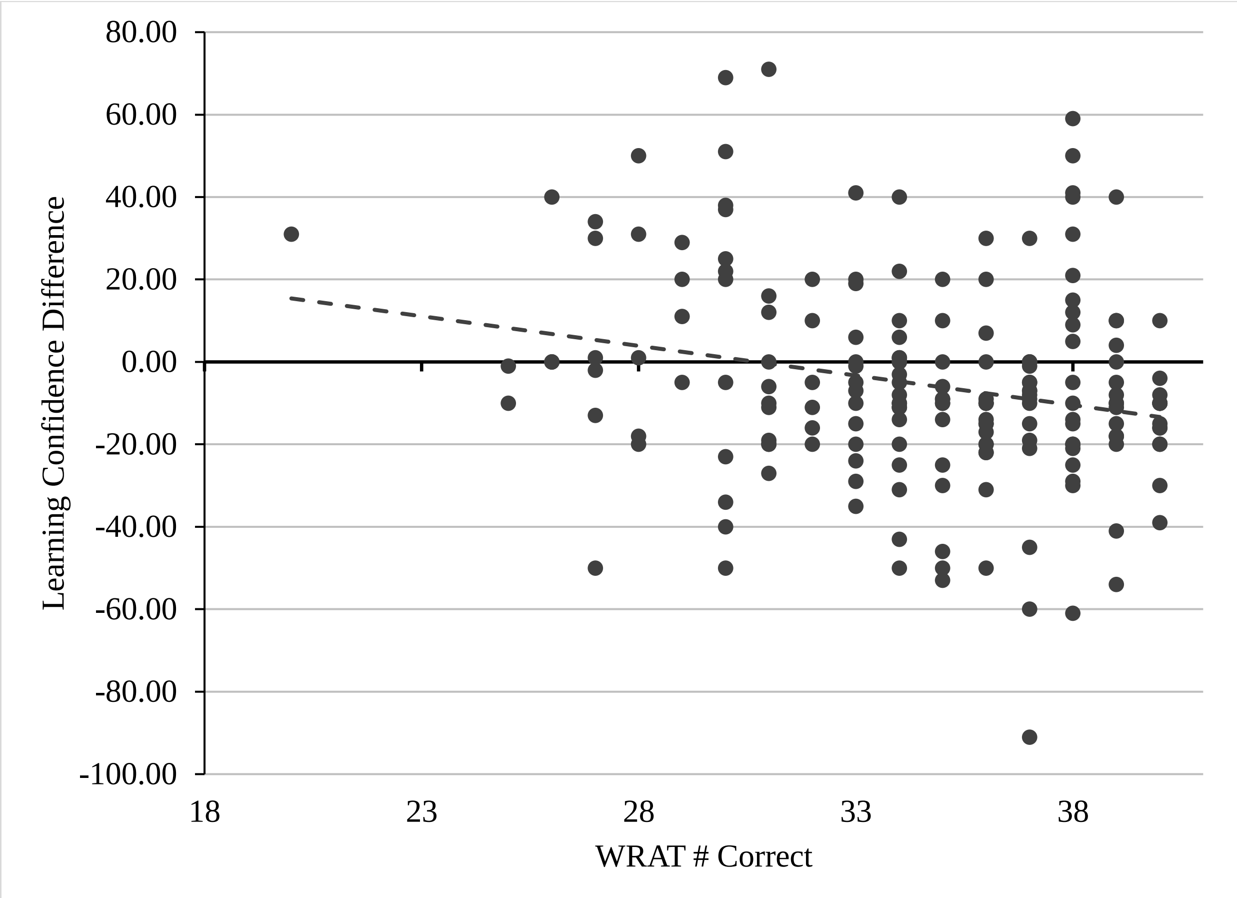


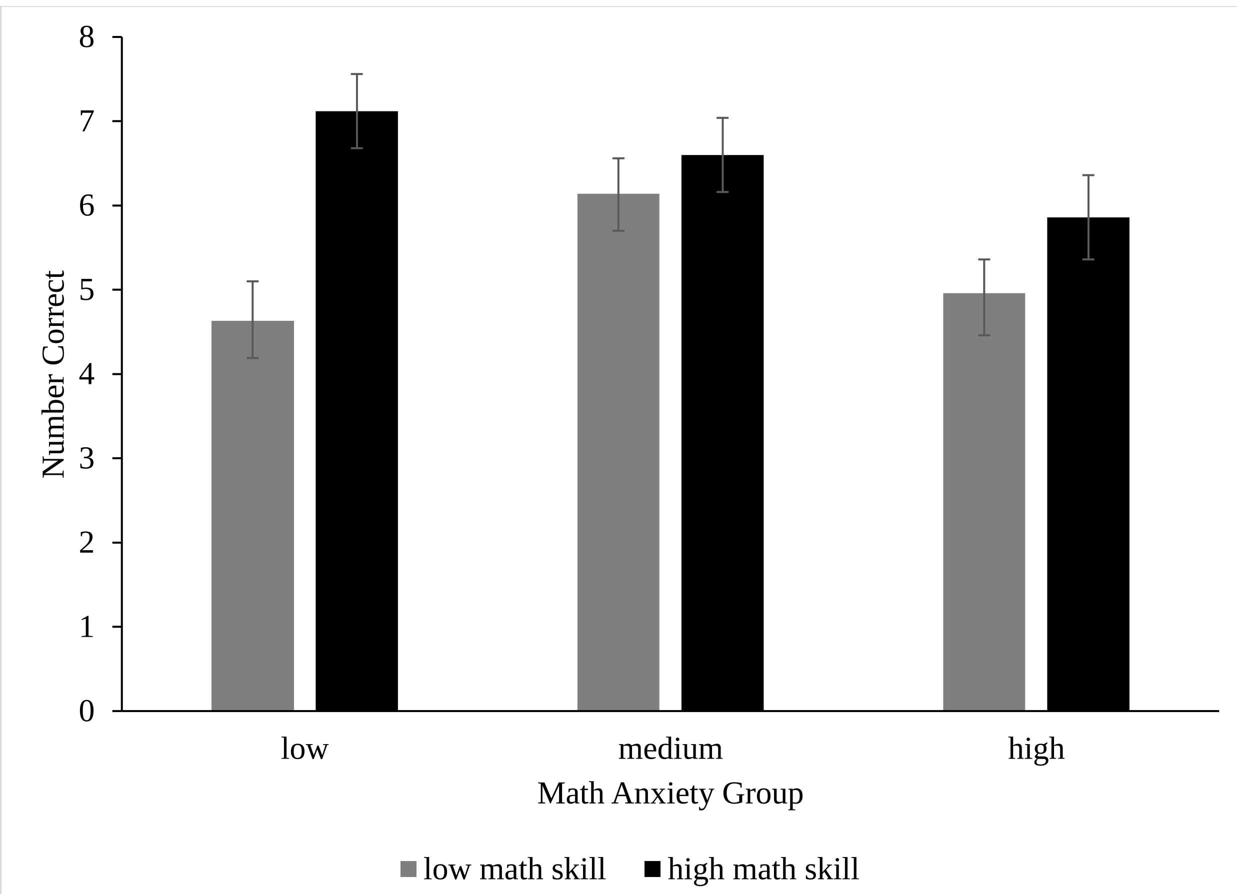
Figure 1.4 Learning Confidence Change from Pre to Post-task by Math Skill



Exploratory Analyses

Accuracy. In further exploring the results, I also decided to convert the math skills into two groups at the median and math anxiety into 3 roughly groups (roughly near the 33^{rd} and 66^{th} percentiles) and analyze the accuracy data with a 2 (worked example vs active problem solving) X 3 (low, medium, and high math anxiety) X 2 (low, medium, and high math skills) ANOVA. There was a significant main effect of math skills $F(1,181) = 11.92$, $p = 0.001$, partial $\eta^2 = 0.06$, such that those with higher math skills scores performed better ($M = 6.53$, $SE = 0.27$) than those with lower math skills scores ($M = 5.24$, $SE = 0.25$). There was a marginally significant math anxiety X math skills interaction, $F(2,181) = 2.85$, $p = 0.06$, partial $\eta^2 = 0.03$. Post-hoc analyses (uncorrected Welch's t-test) reveal that for individuals with low math anxiety, individuals with low math skills performed significantly worse $t(35.16) = -3.39$, $p < 0.01$ than those with high math skills, $M_{low} = 4.64$, $SE_{low} = 0.69$ and $M_{high} = 7.16$, $SE_{high} = 0.27$ respectively, while those with medium and high math anxiety performed similarly whether they were high or low math skilled. In addition, for those in the low skills group, those with low and high math anxiety groups ($M_{low} = 4.64$, $SE_{low} = 0.69$; $M_{high} = 4.90$, $SE_{high} = 0.48$) performed worse than those with medium anxiety $t(40.25) = -2.18$, $p < 0.05$ ($M_{med} = 6.32$, $SE_{med} = 0.34$), while for those in the high skills groups, those with low math anxiety ($M_{low} = 7.16$, $SE_{low} = 0.27$) performed significantly better than those with high math anxiety, $t(37.15) = 2.08$, $p < 0.05$ ($M_{high} = 5.96$, $SE_{high} = 0.51$), see Figure 1.5. No other main effects or interactions were significant.

Figure 1.5 Base Number Conversion Performance by Math Anxiety and Math Skills Groups



I also explored whether problem completion time interacted with math anxiety and math skill to predict performance on the final base number conversion test (*N*=188). I ran a linear regression with number correct on the base number conversion test as the dependent variable sample as a covariate and the following as predictors of interest: study condition, math anxiety, math skill, average problem completion time, problem completion time X condition, problem completion time X math anxiety, and problem completion time X math skill. The full model was significant $F(8,180)=4.59$, $p < 0.001$, $r^2 = 0.17$. Only math skill and problem completion time were significant predictors of accuracy on the base number conversion test, $\beta = 0.21$, $t(180) = 2.77$, $p < 0.01$ and $\beta = -0.24$, $t(180) = -3.02$, $p < 0.01$ for math skill and problem completion time respectively. Higher math skills score and faster problem completion time were associated with greater number correct on the final test. None of the other predictors were significant.

Problem completion time. I also explored completion time further in individuals with high accuracy on the final base number conversion test (7 or 8 correct), $N = 110$. I used the same linear regression model as specified in the previous completion time analysis with sample, group, math anxiety, math skill, and all group, math anxiety, and math skills interactions as predictors. The full model was not significant, $F(8,102) = 1.56$, $p = 0.15$. Math skills was the only significant predictor of problem completion time for those who got 0 or 1 incorrect on the base number conversion test, $\beta = -.25$, $t(102) = -2.51$, $p < 0.05$, with higher math skill associated with faster problem completion. None of the other predictors were significant.

Study 1 Discussion

In summary of study 1, I found that higher math anxiety was associated with worse learning outcomes above and beyond math skill, and that higher math skill was associated with better learning outcomes above and beyond math anxiety. Overall, there did not seem to be any differences in learning outcomes between those who studied using worked examples or those who were in the active problem-solving group, but there was a marginal interaction between study condition and math skill when looking at test performance as a binary outcome. Individuals with lower math skills had were less likely to pass (score 6/8 or higher) the immediate base number conversion test in the worked example group than in the active problem-solving group. I also found that math skill was the only predictor of problem completion time on the immediate base number conversion test, such that higher math skill predicted faster problem completion time. In addition, pre-task confidence in learning and memory predicted a decrease in confidence from pre-task to post-task. Such that the higher one's initial confidence the greater their decline in confidence at the end of session 1. Math skill also predicted change in confidence of learning and memory from pre- to post-task, with higher math skill scores associated with an increase in confidence from the beginning to the end of session 1. There also was an interesting effect of study condition on change in learning confidence, with participants in the worked example group being more likely to report increased confidence in their learning of the base number conversions at the end of session 1 as compared to the beginning.

This first study was an initial look into the intricate interplay between math anxiety, math skill, study strategies and learning of novel mathematics information. I found evidence that math anxiety may present an obstacle to learning new mathematics information above and beyond the difficulty it poses for demonstrating already existing math knowledge. I did not find evidence to suggest any substantial differences in learning outcomes between individuals in the active problem-solving group versus those in the worked example group, even when considering level of math anxiety. However, I did find some evidence that study strategies might interact with individual math skill, such that worked examples might not be as effective in facilitating learning for those with low math skills. It could be that those with low math skills need more practice with new math procedures, or that individuals with low math skills have a more challenging time processing examples, or even both. However, considering that the effect only appears when I assess immediate base number conversion in a pass versus fail manner, I need to replicate the result before pursuing possible reasons that may account for it. Under close inspection, one reason that the two study strategies did not lead to vastly different learning outcomes overall could be due to the close proximity between the learning and test phases of the study. I attempt to explore this issue further in study 2.

Study 2 Methods

In study 1, both individuals in the worked example and active problem-solving groups completed eight base number conversion problems shortly after learning the topic during the immediate test. The immediate test provides additional practice for everyone, possibly washing out learning differences between the two study strategies. I hypothesized that by removing the immediate test there would be more variance in performance at a one-week follow up, which would allow us to be able to better explore if the two study strategies lead to different learning outcomes, especially for those with high math anxiety.

Participants

136 University of Michigan undergraduates participated for course credit or $20. 11 did not return for the session 2, and 3 did not complete the math skills measure. 122 participants had complete base number conversion task, math anxiety, and math skills data. 99 had never learned base number conversions before, main analyses were run both with and without those who reported learning base number conversions previously. The mean age was 19.57 years (SE = 0.09) and 45.9% (N =56) of the sample was male. 60.7% of participants were in their first year

of college, 24.6% in their second, and the remaining 14.2% were further along in their degrees. 64 participants were assigned to the worked example group and 58 into the active problem-solving group. 75.4% of the sample completed either calculus 1 or higher, 10.7% completed pre-calculus or lower, and 16% reported their last course was statistics (one person did not report their last math course). Of those who had the top third math anxiety scores, 67.44% had completed calculus 1 or higher, 16.28% completed pre-calculus or lower, and 16.28% completed statistics as their most recent quantitative course. Of those who completed calculus 1 or higher, 31.5% had math anxiety scores in the top third. 20.5% of the sample had a social science major, 33.6% STEM major, 19.7% in business, economics, and finance, 26.2% were humanities, arts, or undeclared majors.

Design, Materials, and Procedures

Study 2 used the same design and materials as study 1 with a few exceptions in the protocol. In the base number conversion task during session 1, there was no immediate test; instead, participants took a delayed base number conversion test during session 2, five to seven days after session 1. In addition, participants did not complete the post-task metacognitive questionnaire during session 1. All other aspects of the procedure were the same as that of study 1.

While editing the task for study 2 some errors were made. Of the first 21 participants randomly assigned to the active problem-solving group, 10 completed a version of the task that accidently included one worked example during the practice session of the base number conversion task. While attempting to fix the version of the task with the error, the task was mislabeled, and the next 23 individuals assigned to the active problem-solving condition completed the worked example version of the task and were therefore reassigned to the worked example group. The last 37 participants were assigned to the active problem-solving condition to equalize the sample sizes between worked example and active problem-solving groups. Differences between these samples will be discussed further in the next section.

Study 2 Results

Group Differences and Descriptives

There were no significant differences between individuals who completed the correct version of the active problem-solving task with six practice problems and those who completed the incorrect version with five practice problems and one worked example on number correct and problem completion time. Individuals with the incorrect version of the task were included in the active problem-solving group for all analyses. There were no significant differences between individuals in the worked example and the active problem-solving groups in gender, math skills, and working memory. However, individuals in the active problem solving group were higher in math anxiety (M = 27.14, SE = 0.94) than those in the worked example group (M = 23.55, SE = 0.78), $t(113.58) = -2.95$, $p < 0.01$, which is likely due to the differences in subject recruitment timing for the majority of the active problem solving group. See Table 2.1 for descriptive statistics on all measures. Women had significantly higher math anxiety $t(108.58) = -4.02$, $p < 0.001$, and significantly lower math skill, $t(108.46) = 2.43$, $p < 0.05$, and working memory scores, $t(119.96) = 3.18$, $p < 0.01$, than men, see Table 2.2 for means and standard errors. Due to gender being confounded with math anxiety and math skill, gender was no included as a covariate in the main analyses. Scores on the delayed base number conversion test are skewed to the left, with 36.1% of individuals getting the perfect score of 8 correct, 13.9% scoring a 7, and 13.1% scoring a 6, and the remaining 36.9% scoring 5 or less. Due to the non-normal distribution of score on the immediate test, analyses were conduction using both linear and logistic regression.

Table 2.1 Means and Standard Errors by Condition

Measure	Overall *M*(*SE*)	Worked Example *M*(*SE*)	Active Problem-Solving *M*(*SE*)
Delay Test (# Correct)	5.27 (0.27)	5.75 (0.37)	4.74 (0.40)
Delay Test Problem Completion Time (seconds)	44.66 (1.68)	42.52 (1.90)	47.07 (2.84)
Pre-Task Math Anxiety Sum	25.25 (0.62)	23.55 (0.78)	27.14 (0.94)
Math Skill (WRAT # Correct)	34.72 (0.36)	35.11 (0.36)	34.29 (0.65)
Visuo-Spatial Working Memory (SSPAN Partial Load Score)	29.22 (0.74)	30.05 (0.98)	28.31 (1.13) [*N* =57]
Pre-Task Learning Confidence	66.66 (1.88)	70.67 (2.60)	62.22 (2.62)
Delay-Task Learning Confidence	63.38 (3.06)	68.72 (3.96)	57.48 (4.65)
Pre-Task Memory Confidence	54.28 (2.10)	58.91 (2.87)	49.17 (2.95)
Delay-Task Memory Confidence	59.51 (3.26)	65.72 (4.24)	52.66 (4.90)

Table 2.2 Means and Standard Errors by Gender

Variable	Male *N* =56 *M*(*SE*)	Female *N* =66 *M*(*SE*)
Pre-Task Math Anxiety	22.66 (0.94)	27.45 (0.73)
Math Skill	35.63 (0.37)	33.95 (0.58)
Visuo-Spatial Working Memory	31.66 (0.95)	27.15 (1.05)

Base Number Conversion Learning

Number correct. To explore whether study condition, math anxiety, or math skill influence learning outcomes at a one-week delay, I first ran a linear regression. Since the worked example and active problem groups differed on math anxiety, I ran two models. The first model included math anxiety, math skill, and math anxiety X math skill interaction as predictors of performance on the delayed base number conversion test. Model I was significant, $F(3, 118)$ =

7.88, $p < 0.001$, $r^2 = 0.17$. Math anxiety, $\beta = -0.30$, $t(118) = -3.40$, $p = 0.001$, and math skills, $\beta = 0.21$, $t(118) = 2.01$, $p < 0.05$, were significant predictors of performance on the delayed base number conversion test. Higher math anxiety was associated with decreased performance on the delay test, and higher math skills were associated with increased performance on the delay test. The math anxiety X math skills interaction was not significant. Model II consisted of study condition (WE or APS), math anxiety, math skill, and all interactions (math anxiety X math skill, study condition X math anxiety, study condition X math skill, and study condition X math anxiety X math skill) as predictors of performance on the immediate base number conversion test. The full model significantly predicted delayed performance $F(7,114) = 3.64$, $p = 0.001$, $r^2=0.18$, but the change between model I and II was not significant, $F_{change}(4,114) = 0.55$, $p = 0.7$, $r^2_{change} = 0.02$. In model II, math anxiety was a significant predictor, $\beta = -0.28$, $t(114) = -3.04$, $p < 0.01$, with higher math anxiety scores associated with worse performance on the delayed base number conversion test (see Table 2.3 for all values). Math skills and study condition were not significant predictors of delayed test performance, and neither were any of the interactions. When analyzing the data including only those who reported never learning base number conversions, only math anxiety significantly predicted delayed performance, $\beta = -0.35$, $t(91) = -3.51$, $p < 0.01$ (reported from model II). The p-p plot shows that the residuals were not normally distributed.

Table 2.3 Linear Regression Values Predicting Base Number Conversion Delayed Test Performance

	Model I					*Model II*				
Source	*B*	*SE B*	Β	*T*	*P*	*B*	*SE B*	Β	*T*	*P*
Math Anxiety	-0.13	0.04	-0.30	-3.40	0.001	-0.13	0.04	-0.28	-3.04	0.003
Math Skill	0.15	0.08	0.21	2.07	0.04	0.13	0.08	0.17	1.62	0.11
Math Skill XMath Anxiety	0.00	0.01	-0.02	-0.20	0.85	-0.01	0.01	-0.08	-0.73	0.47
Study Condition	-	-	-	-	-	0.34	0.56	0.06	0.60	0.55
Condition XMath Anxiety	-	-	-	-	-	0.04	0.08	0.04	0.44	0.66
Condition XMath Skill	-	-	-	-	-	-0.06	0.16	-0.04	-0.38	0.71
CondXMathSkill XAnxiety	-	-	-	-	-	-0.02	0.03	-0.10	-0.86	0.39
	$F(3,118) = 7.88$, $p < 0.001$, $r^2 = 0.17$					$F(7,114) = 3.64$, $p = 0.001$, $r^2 = 0.18$ $F_{change}(4,114)=0.55$, $p > 0.05$, $r^2_{change} = 0.02$				

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Due to the bimodal distribution of the scores of the immediate test and non-normality of the residuals in the linear regression, I also analyzed the data using logistic regression. Delay test scores were first converted into a bimodal variable, scores from 0-5 were considered failing and assigned a 0 (36.9%), and scores greater than 5 were assigned a 1 (63.1%). I again used two models as in study 1 analyses and used the same predictors as the linear regressions. Model I included math anxiety, math skills, and math anxiety X math skills interactions as predictors of delayed base number conversion test success. Model I was a significant predictor of passing the immediate test, $\chi2$ (3) = 22.72, $p < 0.001$, Cox & Snell $R^2 = 0.17$ (see Table 2.4 for all values). Both math anxiety, Exp(B) = 0.90, $p < 0.01$, 95% CI [0.84, 0.96], and math skills Exp (B) = 1.15, $p < 0.05$, 95% CI [1.01, 1.31] were significant predictors of passing the delayed base number conversion test. One unit of increase in math anxiety is associated with a decrease in probability of passing the delayed test, while one unit of increase in math skills is associated with an increased probability of passing the delayed test. The math anxiety X math skills interaction was not significant. Model II included study condition, math anxiety, math skills, and all associated interactions in the model. Model II was a significant predictor of passing the delayed base number conversion test, $\chi 2(7) = 26.94$, $p < 0.001$, Cox & Snell $R^2 = 0.20$, but the change between model I and model II was not significant, $\chi 2_{change}(4) = 4.22$, $p = 0.38$. None of the interactions or study group were significant predictors of passing the delayed base number conversion test in model II. When the models were run including only those who had reported never learning base number conversions, only math anxiety was a significant predictor of passing the delayed base number conversion test, Exp(B) = 0.85, $p < 0.05$, 95% CI [0.73,1.00] (reported from model II).

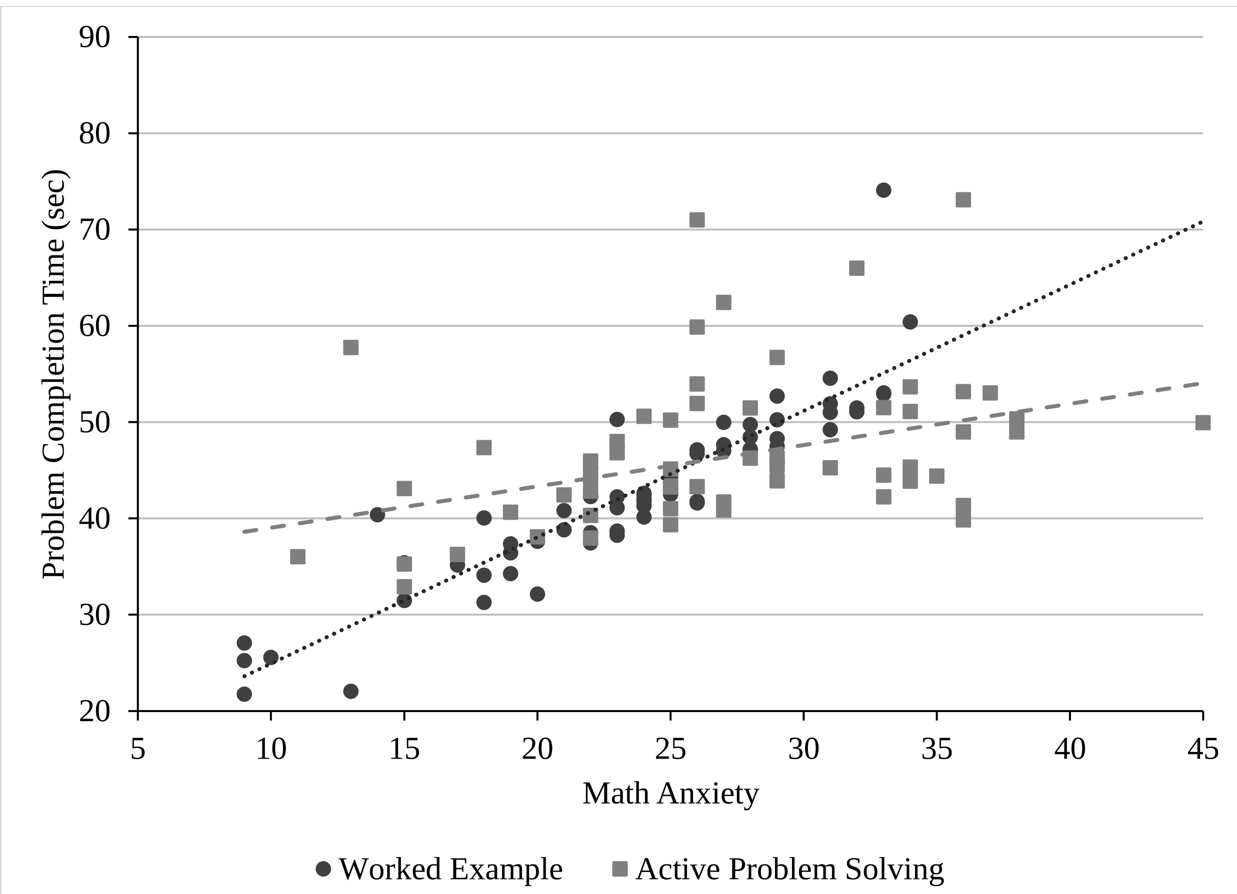
Table 2.4 Logistic Regression Values Predicting Base Number Conversion Delayed Test Performance

	Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B*)
Model I	Math Anxiety	-0.11	0.04	9.20	0.002	0.90	[0.84, 0.96] **
	Math Skill	0.14	0.07	4.57	0.03	1.15	[1.01, 1.31] *
	Math SkillXMath Anxiety	-0.01	0.01	0.28	0.60	1.00	[0.98, 1.02]
			χ^2 (3) = 22.72, $p < 0.001$, Cox & Snell $R^2 = 0.17$				
Model II							
	Math Anxiety	-0.08	0.06	2.16	0.14	0.92	[0.83, 1.03]
	Math Skill	0.14	0.11	1.63	0.20	1.15	[0.93, 1.43]
	Math SkillXMath Anxiety	-0.03	0.02	2.08	0.15	0.97	[0.94, 1.01]
	Study Condition	-0.26	0.45	0.33	0.57	0.77	[0.32, 1.86]
	ConditionXMath Anxiety	-0.05	0.08	0.43	0.51	0.95	[0.82, 1.11]
	ConditionXMath Skill	-0.02	0.14	0.02	0.89	0.98	[0.75, 1.29]
	CondXMathSkillXAnxiety	0.03	0.02	1.96	0.16	1.04	[0.99, 1.09]
			$\chi^2(7) = 26.94$, $p < 0.001$, Cox & Snell $R^2 = 0.20$				
			$\chi^2_{change}(4) = 4.22$, p > 0.05				

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Problem completion time. A linear regression with group, math anxiety, math skill, and all interactions as predictors was used to predict problem completion time on the delayed base number conversion test. There were only completion time data for 121 of the 122 individuals due to loss of the computer files. The full model was a significant predictor of problem completion time, $F(7,113) = 4.02$, $p = 0.001$, $r^2=0.20$. Math anxiety, $\beta = 0.22$, $t(113) = 2.35$, $p < 0.05$, and math skill, $\beta = -0.29$, $t(113) = -2.75$, $p < 0.01$, were significant predictors of completion time. Higher math anxiety scores were associated with longer problem completion time and higher math skill scores were associated with decreased problem completion time. In addition, the study condition X math anxiety interaction was significant, $\beta = 0.20$, $t(113) = 2.26$, $p < 0.05$. Individuals in the worked example group with higher math anxiety scores tended to have higher problem completion times than those in the active problem-solving group (see Figure 2.1). None of the remaining interactions were significant.

Figure 2.1 Problem Completion Time by Math Anxiety and Group



Learning and Memory Confidence

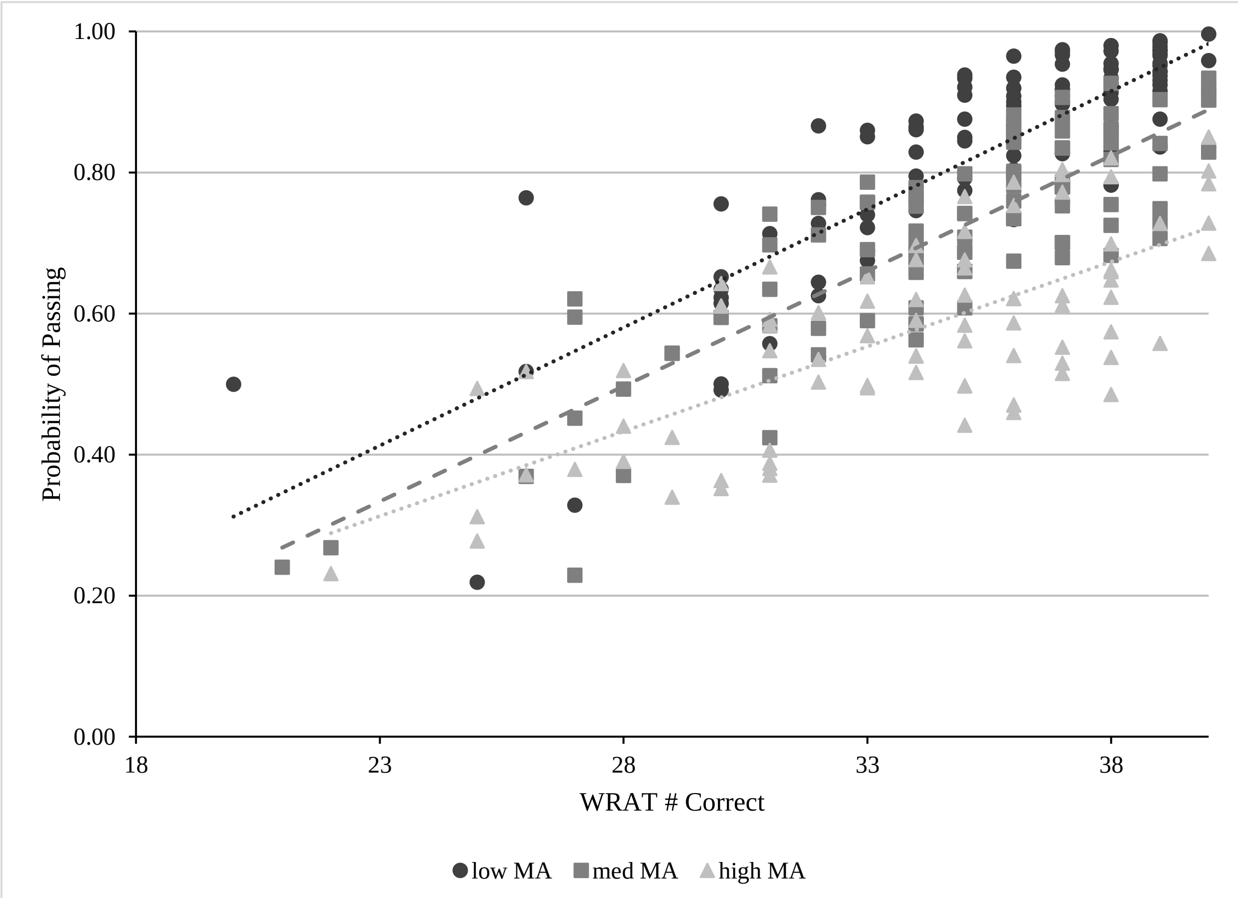
To determine if learning group, math anxiety, or math skill are related to changes in learning and memory confidence scores from before and after learning base number conversions, I calculated a difference score between pre-task and post-task metacognitive measures to use as the dependent measure. The full model included the same predictors as those used in previous linear regressions described with the addition of the pre-task metacognitive scores as a covariate. Two separate models were run, one with learning confidence difference score and the other with memory confidence difference scores as the dependent variable. For learning confidence, the full model was a marginally significant predictor of learning confidence change from the beginning of session 1 to session 2, $F(8,113) = 1.88$, $p = 0.07$, $r^2 = 0.12$. Pre-task learning confidence significantly predicted change from pre-task to post-task in learning confidence, $\beta = 0.27$, $t(113) = 2.67$, $p < 0.01$. Higher pre-task learning confidence was associated with a greater reduction in confidence from session 1 to session 2. Math anxiety score was a marginally significant predictor of learning confidence change, $\beta = 0.21$, $t(113) = 1.94$, $p = 0.06$, with higher math anxiety scores associated with greater reduction in learning confidence scores from session 1 to session 2. No other variables were significant predictors and there were no significant interactions. For memory confidence, the full model was a significant predictor of change in memory confidence from pre-task to post-task, $F(8,113) = 3.05$, $p < 0.01$, $r^2 = 0.18$. Pre-task memory confidence significantly predicted change from pre-task to post-task in memory confidence, $\beta = 0.29$, $t(113) = 3.01$, $p < 0.01$. Higher pre-task memory confidence was associated with a greater reduction in confidence from session 1 to session 2. Math anxiety was a marginally significant predictor of memory confidence change, $\beta = 0.19$, $t(114) = 1.84$, $p = 0.07$, with greater math anxiety associated with greater reduction in memory confidence score from session 1 to session 2. No other variables were significant predictors, and there were no significant interactions.

Study 1 and 2 Combined Analyses

To increase power, I combined both study 1 and 2 data sets. I first ran a linear regression with study as a covariate and study condition, math anxiety, math skill, and all associated interactions as predictors. Performance on the final or delay test was used as the outcome variable. The model was significant, $F(8, 307) = 6.66$, $p < 0.001$, $r^2 = 0.15$. Math anxiety, $\beta = -0.20$, $t(307) = -3.73$, $p < 0.001$, and math skills, $\beta = 0.19$, $t(307) = 4.91$, $p < 0.001$, were significant predictors of performance on the base number conversion test. Higher math anxiety was associated with decreased performance on the delay test, and higher math skills were associated with increased performance on the delay test. None of the interactions were significant.

I also ran a similar model as a logistic regression, with all the same covariate and predictor variables. Scores 5 or under on the final or delay base number conversion test were considered failing and assigned a 0, while scores greater than 5 were considered passing and assigned a 1. The model was a significant predictor of passing the base number conversion test, $\chi 2(9) = 56.33$, $p < 0.001$, Cox & Snell $R^2 = 0.16$. Math anxiety Exp(B) = 0.90, $p = 0.001$, 95% CI [0.85, 0.96], and math skills Exp (B) = 1.26, $p < 0.001$, 95% CI [1.12, 1.41] were significant predictors of passing the delayed base number conversion test. One unit of increase in math anxiety is associated with a decrease in probability of passing the delayed test, while one unit of increase in math skills is associated with an increased probability of passing the delayed test. In addition, the math anxiety X math skill interaction was significant, Exp (B) = 0.98, $p < 0.05$, 95% CI [0.96, 1.00]. Individuals with high math anxiety and low math skill were more likely to fail the base number conversion test than their counterparts with low or medium math anxiety (see Figure 2.2).

Figure 2.2 Study 1 and 2 Combined Math Anxiety by Math Skill



Study 2 Discussion

To summarize, in study 2 I found that math anxiety consistently predicted base number conversion accuracy at a one-week delay, with higher math anxiety associated with lower performance on the delayed test. Math skill was also found to predict base number conversion performance but not in all models, in general higher math skill was associated with higher performance at a one-week delay. With respect to problem completion time, I again found that math anxiety and math skill predicted problem completion time. With higher math anxiety being associated with slower completion time, and higher math skill being associated with faster completion time. I also found that study condition interacted with math anxiety, such that those with high math anxiety in the worked example group tended to take more time to complete base number conversion problems than their counterparts in the active problem-solving group. For learning and memory confidence, I found that pre-task confidence predicted a decline in confidence scores from session 1 to session 2, with higher pre-task confidence predicting a greater the reduction in confidence by session 2. Math anxiety also predicted a decline in confidence scores from session 1 to session 2, with higher math anxiety being associated with a greater reduction in confidence in both learning and memory by session 2.

Other than in problem completion time, I did not find any notable differences between those in the active problem and worked example groups. It is possible that the two conditions do not lead to any notable differences in learning outcomes, especially considering that the sample is relatively high achieving and most individuals did fairly-well on the base number conversion task. However, I did find that individuals with high math anxiety were slower to complete problems at a one-week delay in the worked example condition than their active problem counterparts. This might suggest that more practice is needed during study to achieve a certain level of fluency at a delay for individuals with high math anxiety. Still, there were several methodological errors committed while running the study which may have diluted the differences between the two conditions, e.g. some active problem-solving group participants received one worked example, and many active problem-solving group members were collected at the tail end of data collection. Currently, I cannot make any certain conclusions about the effects of active problem solving versus worked examples on learning for those with high math anxiety. This is discussed further in the general discussion below.

General Discussion

Study 1 and 2 were gave us our first look into the relationships between math anxiety, math skill, study strategies, and learning of new math content. Below I will present our overall findings as organized by the objectives stated at the beginning of the chapter.

Math Anxiety and Learning

Objective 1 of the current study was to determine the influence of math anxiety on learning of new procedural math content, above and beyond general math skill. Here I found that math anxiety had a generally negative effect on learning (or re-learning) of procedural content above and beyond individuals' performance on a general math skills measure, both immediately and at a one-week delay. These findings suggest that math anxiety leads to more difficulties in acquiring new mathematics information. As discussed previously, we know that math anxiety leads individuals to underperform on measures of math skill (Ashcraft & Moore, 2009), but it seems that math anxiety either leads to even worse performance on new content (above and beyond what we see in general math skills measures) or interferes with the actual learning of new math procedures. If individuals with math anxiety merely had difficulty producing their knowledge on the immediate base number conversion test, I would expect that only the math skills and not math anxiety to be a significant predictor of performance. However, since math anxiety predicted performance on the immediate and delayed base number conversion tests, above and beyond math skill, this suggests that math anxiety posed some extra difficulties with the new material.

The reasons for why math anxiety could lead to worse performance on new content cannot be directly addressed by the current study. It could be that since learning new information is more cognitively demanding than retrieving existing knowledge, individuals with high math anxiety are more prone to the negative cognitive effects of math anxiety. According to the processing efficiency theory (Eysenck & Calvo, 1992), if individuals with high math anxiety are preoccupied with worries about their performance they will have less working memory resources available to dedicate to the learning of the new material. This may slow down their ability to create an accurate mental representation and achieve fluency of the new procedure, making them more prone to errors. In contrast, when dealing with pre-existing knowledge, presumably the mental representation already exists, therefore math anxiety is only interfering with the production of the information. The same explanation would fit for the hypothesized attentional control mechanism of math anxiety, such that if individuals with high math anxiety are having difficulty attending to the appropriate information this will also make it more difficult to effectively learn the material at hand.

Either way, both studies thus far demonstrate that math anxiety makes learning new math information more difficult. This finding adds more complexity to our current understanding of how math anxiety leads individuals to opt out of higher math education. It is not merely that individuals with high math anxiety tend to score lower on measures of achievement, but that they have difficulty in acquiring new information compared to their less anxious counterparts. This difficulty in acquiring new math information might become more compounded overtime. Most math curriculum builds off of previous math knowledge, if individuals with high math anxiety do not master certain math topics they are likely up for a difficult path as topics become more and more complex. These findings suggest that we need to focus our interventions not only on reducing the negative performance effects of math anxiety but also finding strategies to help individuals with math anxiety learn new information successfully.

Study Strategies and Learning Outcomes

Objective 2 was to determine the efficacy of worked examples versus active problem solving as study strategies for individuals that differ in math anxiety and math skill. Overall, worked examples and active problem-solving seemed to be equally effective study strategies. However, I did find some evidence that worked examples might not be as effective a study strategy for individuals with low math skills, and that they might be related to less problem-solving fluency for individuals with high math anxiety. It could be that individuals with lower math skills simply need more opportunity to practice new math procedures, but it is also possible that those with lower math skills might not be processing the information in the worked examples as well as their counterparts who have higher math skill.

Based on the long-term memory literature discussed previously, we know that retrieval practice is much more effective for long-term retention than is re-reading (Bertsch et al., 2007). Worked examples present the individual with multiple pieces of information at one time, and the individual must be able to process those pieces of information in a certain way for them to make sense, essentially it is equivalent to re-reading. Individuals with low math skill might not be able to easily make sense of the information presented, possibly spending time attending to the wrong pieces of information, and likely having difficulty staying engaged with the material. In contrast, when completing a practice problem, individuals might be more likely to focus their attention on what they need to complete for each step, and while retrieving each step they are strengthening their memory of it, making it more likely to be remembered at a later time. This could also explain why individuals with high math anxiety in the active problem-solving group tended to have faster problem completion times than those in the worked example group. According to Atkinson, Derry, Renkl, & Wortham, (2000), worked examples need to be carefully designed in order to be effective for learning, such that they emphasize conceptual structure and promote self-explanation, both are characteristics that traditional examples often used in the classroom and math textbooks (such as those used in this study) are unlikely to demonstrate. However, the study condition X math skill effect in accuracy was only marginal in one analysis (study 1), and the study condition X math anxiety effect on problem completion time at a delay (study 2) could be a product of the several methodological errors (for one, the active problem-solving group had higher visuo-spatial working memory scores). To be confident that worked example are indeed less effective for individuals with low math skill and high math anxiety, the finding needs to be replicated in future samples. However, if replicated this could have important implications in the classroom as far as the study strategies we may suggest for students with low math skill or high math anxiety.

Confidence in Learning and Memory

Lastly, objective 3 was to determine if there are differences in learning confidence based on individual’s math anxiety, math skill, and study strategy group. Overall, I found that confidence in both memory and learning of the base number conversion procedure tended to decrease more the higher the initial confidence, both by the end of session 1 and at a one-week delay. This effect could simply be regression towards the mean, however, this trend is common in many studies that use judgements of learning, such that individuals tend to become less confident with subsequent learning experiences (Koriat, Sheffer, & Ma’ayan, 2002). The latter is likely due to the experience of attempting to recall information. Before one has attempted to recall information, there is often an illusion of knowing leading many to be overconfident, but after experiencing recall, the individual becomes more aware of the gaps in their knowledge, leading them to lower their confidence for later recall of the material.

In study 1 I found that math skill and study condition predicted confidence change (with individuals in the worked example group reporting an increase in learning confidence from pre-task to post task), but in study 2 I only found that math anxiety predicted confidence change.

This could be due the variation of the salience of these cues in the different studies. Math skill and study condition might be the more salient cues at the end of session 1 in study 1 based on subjective ease of the experience. Everyone did fairly well on the base number conversion task, it might be that after this success experience individuals with high math skill felt validated and therefore more confident in their learning and memory of the material. In addition, we know that retrieval practice feels more effortful, therefore, individuals in the worked example group might have subjectively viewed their experience as rather easy because they did not have to solve as many problems during learning. In contrast, in study 2 participants did not complete a test of their base number conversion knowledge till one-week after their learning session, this may make their math anxiety the most salient cue at that point in time. However, we would need to run an experiment in which we can directly compare individuals who made confidence judgements at different times to assess what factors specifically contributed to their judgments. Overall, these findings suggest that math anxiety might not necessarily drive individual confidence on the day of learning, but more so when individuals have to demonstrate learning at a later time without opportunity to review the material.

Conclusion

In conclusion, we found evidence that math anxiety poses an obstacle to learning new math material, and that worked examples might be a less effective study strategy for individuals with low math skills or high math anxiety. However, the former is a much more reliable finding than the latter. We also found that different cues might be used to predict confidence in learning of new materials, with individual math anxiety being more strongly associated with confidence at a delay after learning. However, two main factors limit our ability to generalize these findings. One is the lack of variance in the outcome measure used, with the majority of individuals performing almost at ceiling on the base number conversion task. The second is the lack of distinctiveness between the worked example and active problem-solving groups. The reality is the difference between studying three problems and solving three problems in the worked example group versus solving six problems in the active problem-solving group is not that drastic, even though this is the format previous studies have assessed worked examples before. In the next chapter, I aim to replicate these findings and address these two limitations presented.

CHAPTER III

Math Anxiety, Math Skill, and Study Strategies Part II

In contrast to previous research, we did not find any evidence to support the view that studying worked examples leads to learning outcomes different than completing practice problems for study overall and found only minimal evidence to suggest that worked examples might not be an effective learning strategy for individuals with low math skill or high math anxiety. The lack of strong, consistent findings in the first two studies suggests a lack of distinctiveness between using worked examples and active problem solving as study strategies, at least in the manner in which they were used in our study. After all, even individuals using the worked example study strategy solve some practice problems. In the current study, I aim to expand our previous exploration of study strategies to include not only worked example and active problem-solving groups but also a group which studies using a hybrid of worked examples and active problem solving which we will refer to as the faded examples, and a group which studies only examples and completes no practice problems.

My first objective is replicate the findings from the previous chapter, specifically the effects of math anxiety on learning outcomes and the study condition by math skill interaction, where we found that individuals with low math skill in the worked example group were less likely to pass the immediate base number conversion test than their counterparts in the active problem-solving group. My second objective will be to determine if faded examples are a more effective study strategy than traditional worked examples, especially for individuals high in math anxiety or low in math skill. Lastly, my third objective will be to determine if studying examples only lead to worse learning outcomes compared to both worked example and active problem-solving conditions, especially for those with high math anxiety or low math skill.

Renkl, Atkinson, Maier, & Staley, (2002) suggest that faded examples could be more effective in facilitating learning, since they provide a more seamless transition from example to practice problem. The use of faded examples consists of a strategic ordering of problems which provide less and less support as one progresses through the problem set. For example, one would start by studying a complete worked example then be presented with increasingly incomplete examples till the individual is eventually solving problems independently. Faded examples have been found to lead to more favorable learning outcomes than do worked examples (Renkl, Atkinson, & Große, 2004; Renkl et al., 2002). Faded example have several advantages compared to traditional worked examples and solving practice problems. For one, faded examples are more engaging. In a traditional worked example there is no reason for the individual to engage in processes other than simply reading through the example, however, in a faded example the individual must engage with the material to complete the missing step. Another advantage is that in a faded example the individual receives the benefit of retrieval practice but without the full cognitive burden of having to complete an entire practice problem independently. Considering that individuals with high math anxiety are more likely to burden their working memory resources or have difficulties in attentional control, faded examples could be the ideal manner to support their learning. I hypothesize that individuals with high math anxiety or low math skill in the faded example group will outperform their counterparts in the worked example group.

As far as previous literature, there is no work that I know of that has assessed the procedural learning outcomes of individuals who study a math task using only examples without practicing completing the problems themselves. I believe that this is an important missing component of the current literature, in that previous worked example research does not allow us to differentiate fully the contributions of examples versus practice problems in learning. I hypothesize that using examples only during study will lead to worse learning outcomes than either worked examples or active problem-solving strategies, especially for individuals with low math skill and high math anxiety.

Methods

Participants

252 University of Michigan undergraduate students participated either for credit or for $20. 18 people did not return for session 2, 2 did not complete session 1, 12 did not complete the working memory task, and 1 was missing the math skills measure. 231 students had complete data for math anxiety, math skill, and the base number conversion learning task. Participants were told multiple times that they must have not learned base number conversions in the past to be eligible for participation. Still of the 231, only 218 had confirmed during session 1 that they never learned base number conversions before. It is unclear whether the remaining participants had actually learned base number conversions before, considering the number of times they were notified of the eligibility requirements throughout the study. There were no significant differences in accuracy between those who had learned base number conversions previously and those who were novices, but those who reported having learned it before were faster (M = 23.51, SE = 11.64) than those who had not (M = 33.41, SE = 1.17), $t(15.35) = -2.88$, $p < 0.05$, so all main analyses were run both with and without those who had learned base number conversions previously. Of the 231, 42.4% (N = 98) were male with the average age of 19.65 years (SE = 0.24). 53.2% of the sample were in their first year of college, 12.1% in their second, and the remaining 34.7% were further along. 60 were randomly assigned to the worked example group,

59 to the faded example, 61 into the active problem solving, and 51 individuals into the examples only condition. 67.5% of the sample completed either calculus 1 or higher, 17.3% completed pre-calculus or lower, and 15.2% reported their last course was statistics. Of those who had the top third of math anxiety scores, 59.31% had completed calculus 1 or higher, 26.37% completed pre-calculus or lower, and 14.29% had completed statistics as their most recent quantitative course. 36.4% of those who completed calculus 1 or higher had math anxiety scores in the top third. 35.1% of the sample had a social science major, 27.7% were a science, technology, engineering, or mathematics major, 13.9% were in business, economics, or finance, and 23.4% were humanities, arts, or undecided majors.

Design

Study design was similar to that of Study 1 (see Chapter 2) with a few modifications to the base number conversion task, the math task being presented on Qualtrics instead of EPrime, and the addition of task related anxiety and study habits questions. Participants were randomly assigned into one of four (instead of the previous two) study conditions: worked example, active problem solving, faded example, and example only. The rest of the study used the same measures and followed the same procedure as Study 1.

Materials

Base number conversion task. The base number conversion task was very similar to that used in Study 1 with a few changes to the study and test phases of the study. After watching the 10-minute base number conversion video, participants were randomly assigned into one of the four study conditions. The first change was the addition of the faded example and the example only conditions. The faded example condition is a hybrid between worked example and active problem-solving conditions. The first problem presented was a full worked example. For the next problem, participants were asked to complete the first step of the procedure, and after responding they were shown the rest of the example. In the third problem they were to complete the first two steps before being presented with the rest of the example. This pattern was followed for the first five problems, leading up to the last three practice problems which the participants completed without any scaffolds. The example only condition was added to mirror the active problem-solving condition and to assess how learning is influenced if participants were not presented with any opportunity to practice the algorithm independently. The second difference is the addition of two more difficult problems to the practice and test phases of the study. The two added problems were different from the previous problems, instead of converting a number from base 10 into a base smaller than 10, the participants had to convert from base 10 into a base greater than 10. The third difference was the change of the problem order, the worked examples condition was altered to mirror the order used for the faded example condition. Instead of the examples and practice problems being interleaved, the first five problems were examples to-be-studied and the last three problems were problems to-be-solved. This was done to ensure that the last three to-be-solved practice problems were the same across the worked example, faded example, and active problem-solving conditions. All conditions, except for the active problem-solving condition, presented participants with at least one example of the more difficult problem type, those that asked participants to convert a number in base 10 into a base greater than 10. Other than these modifications the math task was the same as that used previously. For the problems presented, see Appendix 2.

Math anxiety, metacognitive questionnaire, working memory, and math skills. Please refer to the descriptions of these measures provided in Study 1.

Task behaviors questionnaire. A series of items were added halfway through data collection (*N* = 111) to assess individuals' affect at the end of session 1. Participants completed the following items:

- Frequency of off-task thoughts: On a scale of 1 to 5, 1 being "not at all" and 5 being "very often rate how often you had distracting, off-task thoughts during the following circumstances.
    - While you were viewing the video and studying the examples
    - While you were completing base number conversion problems
- Content of off-task thoughts: Use the sliding scale from 1-100 to respond to the following questions
    - What percent of your off-task thoughts were related to worry of nervousness about your performance?
    - What percent of your off-task thoughts were related to negative feelings about mathematics?
- Task specific anxiety: On a scale of 1 to 5, with 1 being "not anxious" and 5 being "very much anxious", rate how anxious you felt during the following circumstances (since $\alpha = 0.92$, a sum score was used for any analyses).
    - Participating in this experiment
    - Watching the video about base number conversions
    - Learning base number conversion
    - Studying examples of base number conversions
    - Completing base number conversion problems
    - Your performance on the task

I also included an open response question that asked participants to tell us a little bit about how they felt during the study.

Procedures

The order of the tasks was identical to that in Study 1 with the addition of the task behaviors questionnaire at the end of session 1.

Results

All t-tests reported are Welch's t-test unless otherwise stated.

Group Differences and Descriptives

There were no significant differences between individuals in the four groups group in gender, math anxiety, math skill scores, visuo-spatial working memory, off task thoughts, or task specific anxiety. However, there was a marginal difference in age between groups $F(3,227) = 2.43$, $p = 0.07$, individuals in the examples only group were 20.80 years old (SE = 0.86) while they were 19.23 (*SE* = 0.28), 19.19 (*SE* = 0.24), and 19.56 (*SE* = 0.36) years old in the worked example, faded examples, and active problem-solving group respectively. For overall and group descriptive statistics see Table 3.1. Women had significantly higher math anxiety scores $t(221.17) = -3.00$, $p < 0.01$ than men, more off-task thoughts related to worry/nervousness about their performance $t(102.30) = -4.10$, $p < 0.001$, greater task specific anxiety $t(104.82) = -3.11$, $p < 0.01$, and marginally lower math skills scores $t(210.62) = 1.80$, $p = 0.07$, see Table 3.2 for means and standard errors. Since gender was confounded with math anxiety, gender was not included as a covariate in the main analyses. Overall, individuals reported having off-task thoughts more often during the video and while studying examples than when completing base number conversion problems, $t(110) = 8.69$, $p < 0.001$. Math anxiety was associated with increased anxiety during the math task and increased frequency of off-task thoughts. For correlations between math anxiety, off-task thoughts, and task specific anxiety see Table 3.3. Scores on the immediate base number conversion test were skewed left with 11.3% of the sample receiving the perfect score of 10 correct, 6.9% receiving 9, 30.3% receiving an 8, 17.3% with a 7 and the remaining 34.2% receiving scores of 6 or less. Due to the non-normal distribution of score on the immediate test, analyses were conducted using both linear and logistic regression.

Table 3.1 Means and Standard Errors by Condition

Measure	Overall *M*(*SE*)	Worked Example *M*(*SE*)	Faded Example *M*(*SE*)	Active Problem-Solving *M*(*SE*)	Example Only *M*(*SE*)
Immediate Test (# Correct)	6.33(0.20)	6.52(0.42)	6.31(0.41)	6.16(0.38)	6.35(0.44)
Immediate Test Problem Completion Time(seconds)	32.85(1.13)	28.06(1.42)	27.88(1.37)	33.51(2.63)	43.45(2.81)
Pre-Task Math Anxiety Sum	25.03(0.49)	25.78(0.99)	25.29(0.99)	24.44(0.95)	24.53(1.02)
Math Skill (WRAT # Correct)	33.66(0.27)	33.52(0.54)	33.83(0.51)	34.26(0.51)	32.90(0.63)
Visuo-Spatial Working Memory (Partial Load Score, *N* = 218)	30.83(1.48)	29.90(1.05)	29.97(0.85)	34.46(5.72)	28.85(1.15)
Pre-Task Learning Confidence	61.42(1.54)	63.10(2.97)	62.69(2.99)	62.74(3.00)	56.37(3.39)
Post-Task Learning Confidence	58.16(1.89)	61.07(3.97)	63.49(3.46)	52.30(3.80)	55.45(3.77)
Pre-Task Memory Confidence	49.71(1.50)	51.83(2.96)	47.32(2.94)	51.21(2.90)	48.16(3.22)
Post-Task Memory Confidence	51.19(1.90)	53.40(3.81)	52.17(3.55)	47.75(4.01)	51.49(3.85)
Frequency off-task thoughts-video/examples (*N=111)*	2.78(0.11)	2.63(0.26)	2.90(0.28)	2.82(0.17)	2.75(0.21)
Frequency off-task thoughts-solving problems (*N=111)*	1.80 (0.10)	1.56(0.27)	2.20(0.29)	1.90(0.15)	1.58(0.15)
% off-task due to nervousness about performance (*N=111)*	27.83(2.80)	25.13(7.41)	25.25(6.41)	30.13(4.77)	27.97(5.12)
% off-task due to negative math feelings (*N=111)*	25.68(2.78)	17.31(6.11)	23.10(6.34)	24.90(4.26)	31.69(5.71)
Task Specific Anxiety Sum (*N=111)*	13.14(0.57)	12.31(1.45)	12.45(1.17)	14.03(1.05)	12.92(1.02)

Table 3.2 Means and Standard Errors by Gender

Variable	Male *N =98* *M*(*SE*)	Female *N =133* *M*(*SE*)
Pre-Task Math Anxiety	23.37(0.69)	26.25(0.67)
Math Skill	34.22(0.41)	33.24(0.36)
Visuo-Spatial Working Memory	30.44(0.79)	31.11(2.52)
Frequency off-task thoughts-video/examples (*N=111)*	2.83(0.18)	2.75(0.13)
Frequency off-task thoughts-solving problems (*N=111)*	1.77(0.16)	1.83(0.12)
% off-task due to nervousness about performance (*N=111)*	16.23(2.75)	36.67(4.16)
% off-task due to negative math feelings (*N=111)*	25.54(4.27)	25.79(3.71)
Task Specific Anxiety Sum (*N=111)*	11.19(0.80)	14.62(0.76)

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Table 3.3 Correlations between Anxiety and Task Behavior Measures

	Task Anxiety	Frequency off-task thoughts-video/examples	Frequency off-task thoughts- solving problems	% off-task due to nervousness about performance	% off-task due to negative math feelings
Math Anxiety	0.60**	0.31**	0.24*	0.43**	0.34**
Task Anxiety	-	0.22*	0.31**	0.59**	0.46**

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Overall Effects

To explore whether math anxiety or math skill influence overall learning outcomes, I ran a linear regression including math anxiety, math skill, and math anxietyXmath skill as predictors with number correct on the final base number conversion test as the outcome variable. The model was significant, $F(3,227) = 13.99$, $p < 0.001$, $r^2 = 0.16$, see Table 3.4. Both math anxiety and math skill were significant predictors of base number conversion performance, $\beta = -0.20$, $t(227) = -3.12$, $p < 0.01$ and $\beta = 0.25$, $t(227) = 3.82$, $p < 0.001$ respectively. Higher math anxiety was associated with lower performance on the final test (Figure 3.1), while higher math skill was associated with higher performance on the final test (Figure 3.2). The math anxietyXmath skill interaction was not significant. When including only those who had never learned base number conversions in the analysis, the full model was still significant, $F(3,214) = 13.98$, $p < 0.001$, $r^2 = 0.16$. Math anxiety and math skill were also significant, $\beta = -0.23$, $t(214) = -3.47$, $p = 0.001$ and $\beta = 0.21$, $t(214) = 3.13$, $p < 0.01$ respectively. In addition, the math anxietyXmath skill interaction was marginal, $\beta = 0.13$, $t(214) = 1.97$, $p = 0.05$. Individuals with low and medium math anxiety tended to perform similarly to each other, with individuals with high math skill performing better than those with low math skill. However, individuals with high math anxiety tended to perform much worse than those with low or medium math anxiety especially when they had lower math skill, see Figure 3.3.

Table 3.4 Linear Regression Values for All Conditions Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Β	*T*	*P*
Math Anxiety	-0.08	0.03	-0.20	-3.12	0.002**
Math Skill	0.19	0.05	0.25	3.82	0.000***
Math SkillXMath Anxiety	0.01	0.01	0.09	1.49	0.14

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Figure 3.1 Base Number Conversion Adjusted Number Correct by Math Anxiety

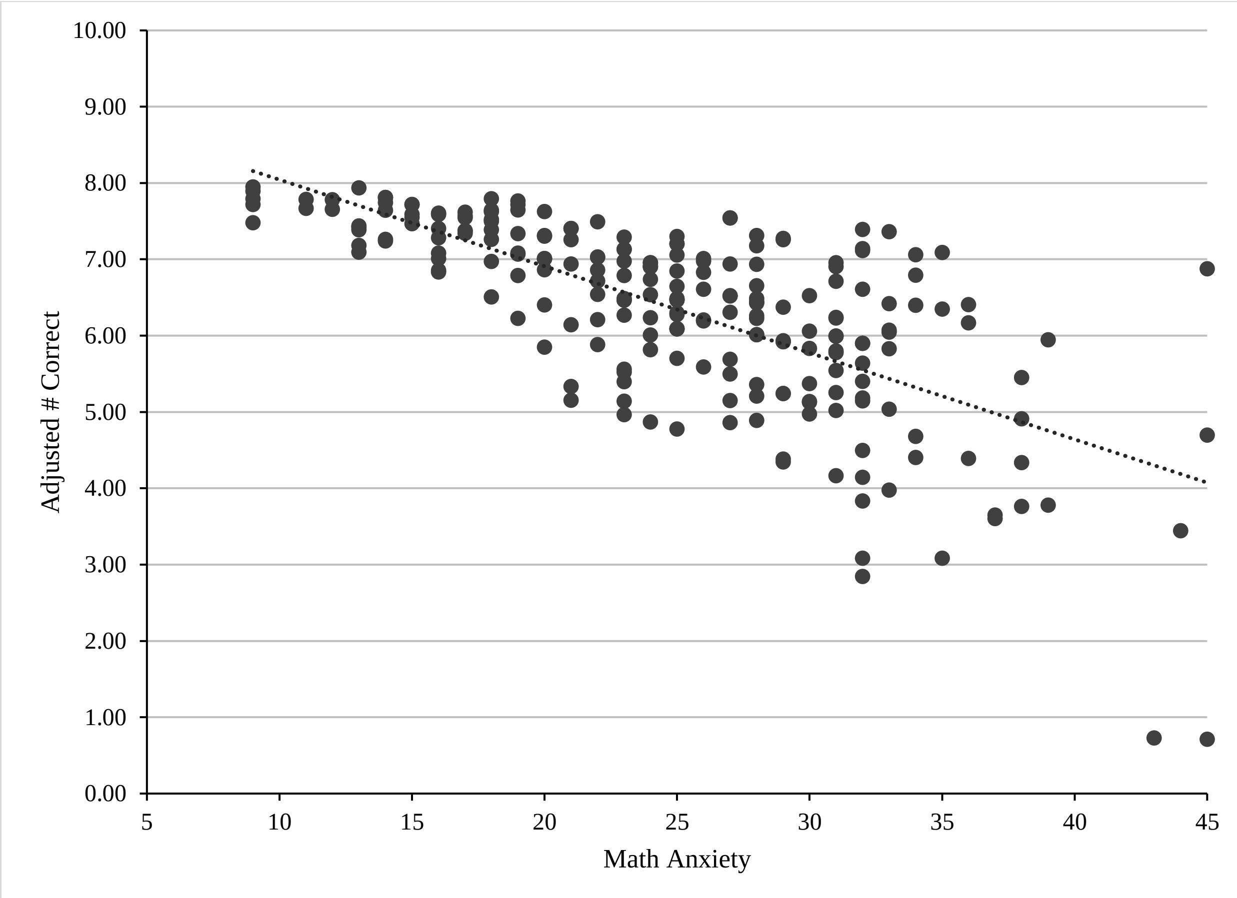


Figure 3.2 Base Number Conversion Adjusted Number Correct by Math Skill

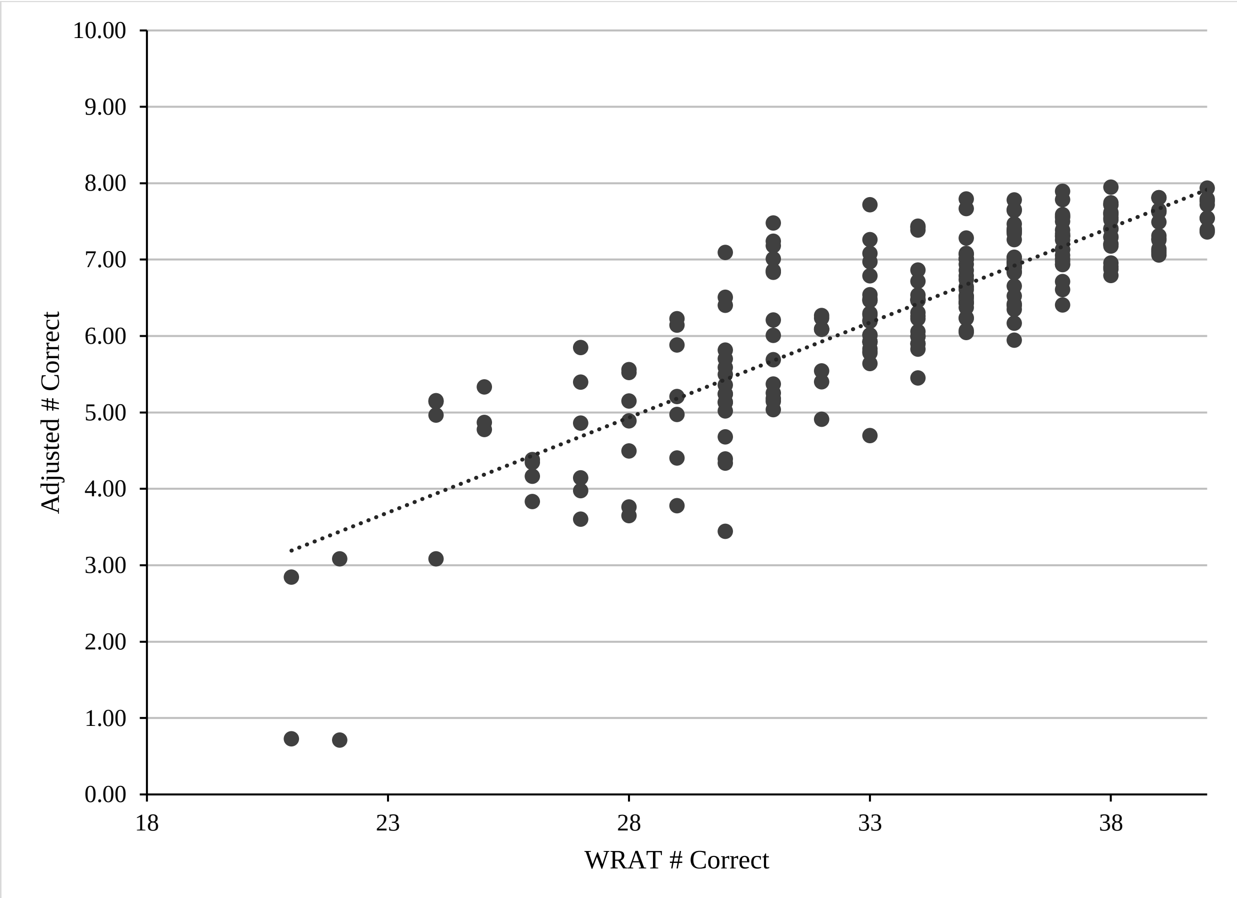
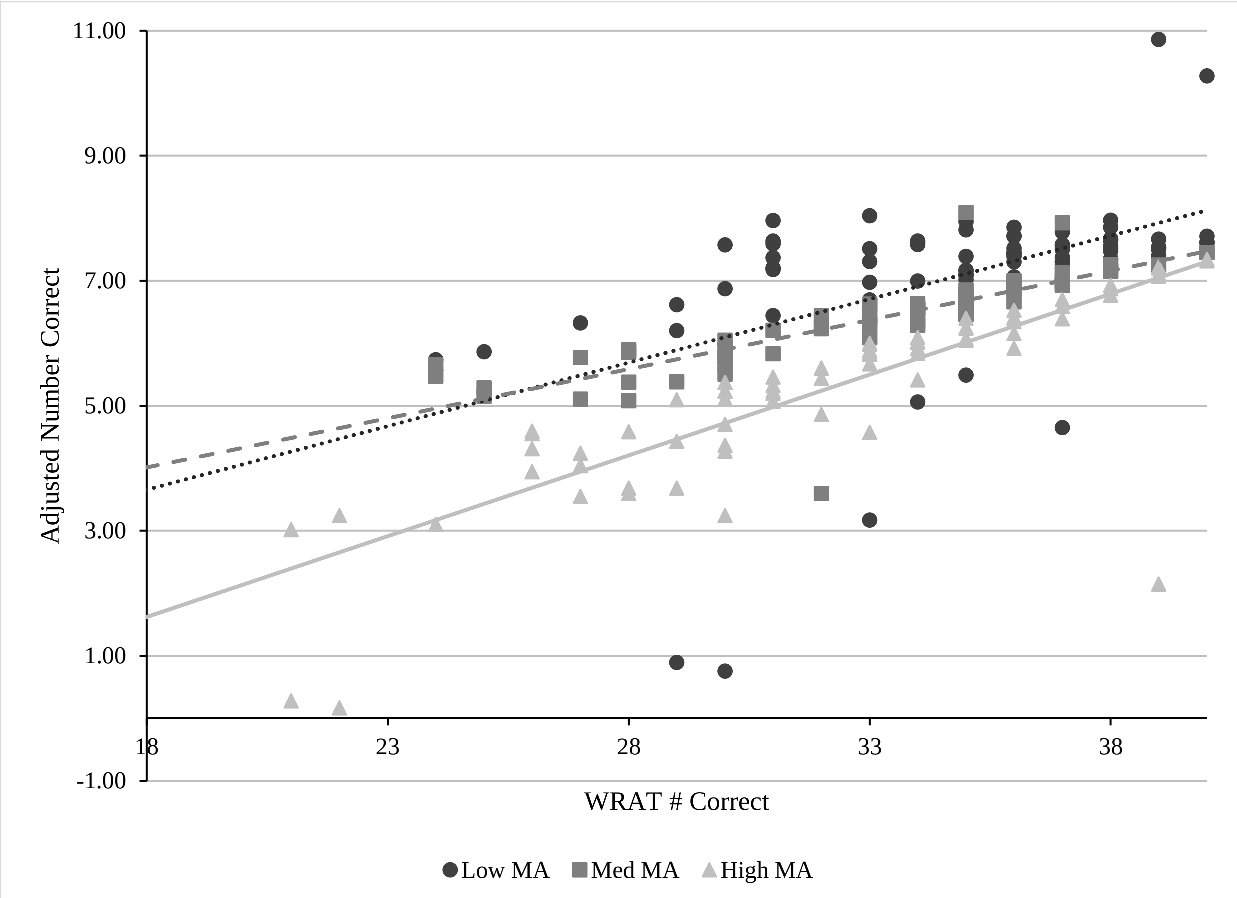


Figure 3.3 Base Number Conversion Adjusted Number Correct by Math Skill and Math Anxiety



The analyses were also run using a logistic regression, scores 6 and below on the final base number conversion test were considered failing and assigned a 0 and scores greater than 6 were considered passing and assigned a 1 (this mirrors receiving a passing grade in a undergraduate course). The full model was significant, χ^2 (3) = 29.33, $p < 0.001$, Cox & Snell $R^2 = 0.12$, see Table 3.5 for all values. Math anxiety and math skill were significant predictors of passing the immediate test, Exp(B) = 0.93, $p < 0.01$, 95% CI [0.90,0.98] and Exp(B) = 1.10, $p < 0.05$, 95% CI [1.02,1.19] respectively. Higher math anxiety was associated with lower chances of passing the final test, while higher math skill was associated with higher chances of passing the final test.

Table 3.5 Logistic Regression Values for All Conditions Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B*)
Math Anxiety	-0.07	0.02	9.41	0.002	0.93	[0.90,0.98]**
Math Skill	0.10	0.04	6.37	0.01	1.10	[1.02,1.19]*
Math SkillXMath Anxiety	0.01	0.01	2.01	0.16	1.01	[1.00,1.02]

+ < 0.08, *<0.05, **<0.01, ***< 0.001

A similar linear regression model was run but with problem completion time as the outcome variable and number correct added as a covariate. The full model was significant $F(4,226) = 3.83$, $p < 0.01$, $r^2 = 0.06$. However, only math skill significantly predicted problem completion time, $\beta = -0.25$, $t(226) = -3.51$, $p = 0.001$, with higher math skill associated with faster problem completion time. No other predictors were significant.

Worked Example Versus Active Problem Solving

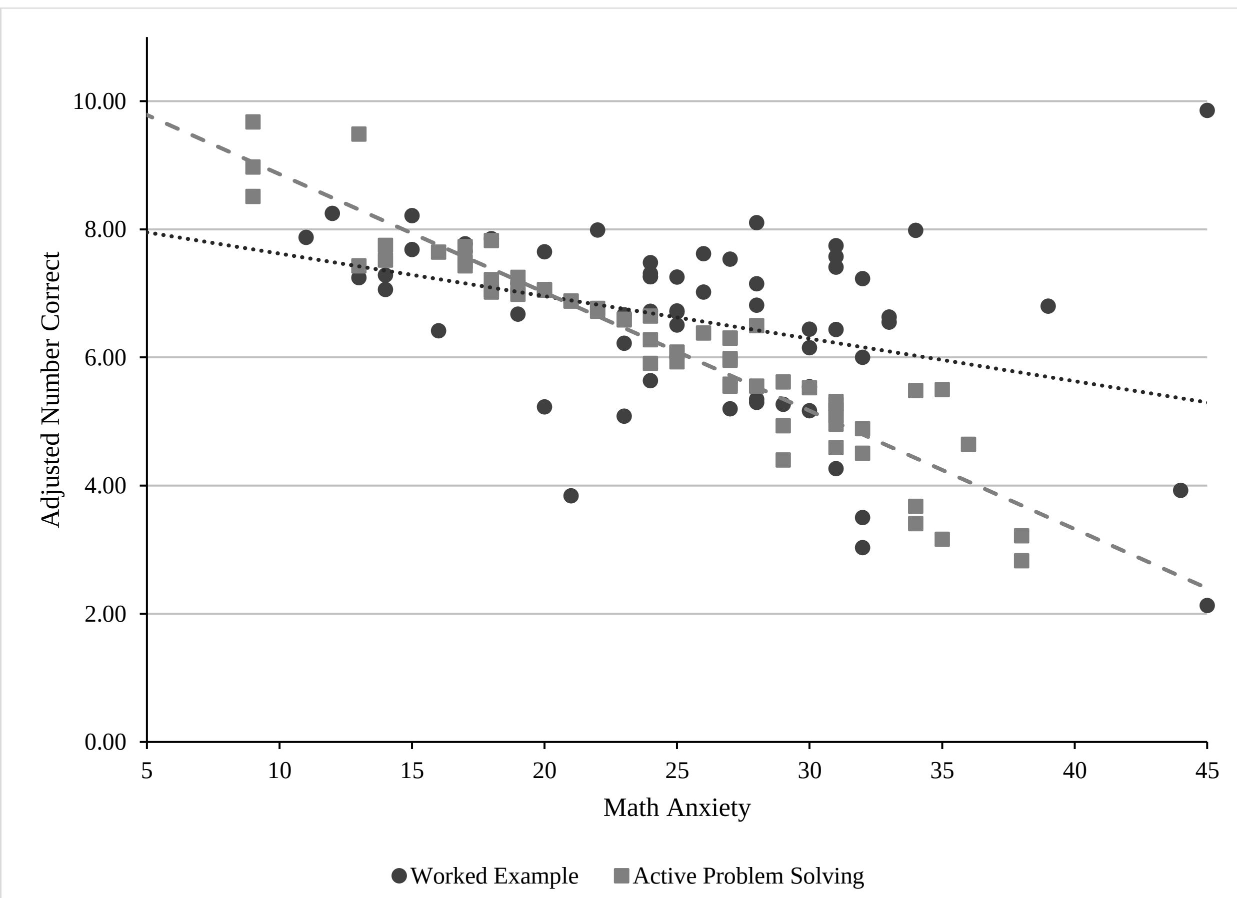
To explore whether studying using worked example versus active problem-solving lead to different learning outcomes along with math anxiety and math skill, I ran a linear regression model including study condition (worked example vs active problem-solving), math anxiety, math skill, and all interactions. The full model was significant $F(7,113) = 4.57$, $p < 0.001$, $r^2 = 0.22$, see Table 3.6 for all values. Both math anxiety and math skill were significant predictors, $\beta = -0.28$, $t(113) = -3.18$, $p < 0.01$ and $\beta = 0.22$, $t(113) = 2.33$, $p < 0.05$ respectively. Higher math anxiety was associated with lower final test performance and higher math skill was associated with higher final test performance. There was also a marginal conditionXmath anxiety interaction, $\beta = -0.16$, $t(113) = -1.84$, $p = 0.07$. Individuals with low math anxiety in the active problem-solving group tended to perform better than those in the worked example group, but individuals with higher math anxiety in the active problem-solving group tended to do worse than those in the worked example group, see Figure 3.4. None of the other predictors were significant. I also ran the model including only those who reported they had never learned base number conversion. The full model was significant $F(7,107) = 4.23$, $p < 0.001$, $r^2 = 0.22$. Math anxiety and math skill were still significant and the study conditionXmath anxiety interaction still marginal.

Table 3.6 Linear Regression Values for Worked Example and Active Problem-Solving Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	β	*T*	*P*
Study Condition	-0.42	0.54	-0.07	-0.77	0.44
Math Anxiety	-0.12	0.04	-0.28	-3.18	0.002**
Math Skill	0.16	0.07	0.22	2.33	0.02*
Math SkillXMath Anxiety	0.01	0.01	0.13	1.43	0.16
Study CondXMath Anxiety	-0.13	0.07	-0.16	-1.84	0.07+
Study CondXMath Skill	-0.21	0.14	-0.14	-1.52	0.13
Study CondXMath AnxietyXMath Skill	0.01	0.02	0.06	0.57	0.57

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Figure 3.4 Base Number Conversion Adjusted Number Correct by Math Anxiety



For the logistic regression, the full model was significant, χ^2 (7) = 30.08, $p < 0.001$, Cox & Snell $R^2 = 0.22$, see Table 3.7. Math anxiety was a significant predictor of passing the immediate test, Exp(B) = 0.87, $p < 0.01$, 95% CI [0.80,0.95], with higher math anxiety being associated with lower chances of passing the final base number conversion test. In addition, the study conditionXmath anxiety interaction was significant, Exp(B) = 0.77, $p < 0.01$, 95% CI [0.64, 0.93]. The interaction was the same as that found in the linear regression; individuals with low math anxiety were more likely to pass in the active problem-solving group than in the worked example group, but those with high math anxiety were less likely to pass in the active problem-solving group than in the worked example group, see Figure 3.5. In addition, the math anxietyXmath skill interaction was marginal, Exp(B) = 1.02, $p = 0.07$, 95% CI [1.00,1.04]. Individuals with low and medium math anxiety had similar likelihood of passing the final test, with likelihood of passing increasing with math skill. However, those with low math anxiety had a much lower likelihood of passing especially when they had lower math skill, see Figure 3.6. No other predictors were significant.

Table 3.7 Logistic Regression Values for Worked Example and Active Problem-Solving Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B*)
Study Condition	0.07	0.52	0.02	0.90	1.07	[0.39,2.95]
Math Anxiety	-0.14	0.05	8.95	0.003	0.87	[0.80,0.95]**
Math Skill	0.02	0.06	0.09	0.76	1.02	[0.90,1.16]
Math SkillXMath Anxiety	0.02	0.01	3.34	0.07	1.02	[1.00,1.04]+
Study CondXMath Anxiety	-0.26	0.09	7.77	0.005	0.77	[0.64,0.93]**
Study CondXMath Skill	-0.19	0.13	2.09	0.15	0.83	[0.65,1.07]
Study CondXMath AnxietyXMath Skill	0.02	0.02	0.61	0.44	1.02	[0.98,1.06]

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Figure 3.5 Probability of Passing by Math Anxiety for Worked Example and Active Problem-Solving Groups

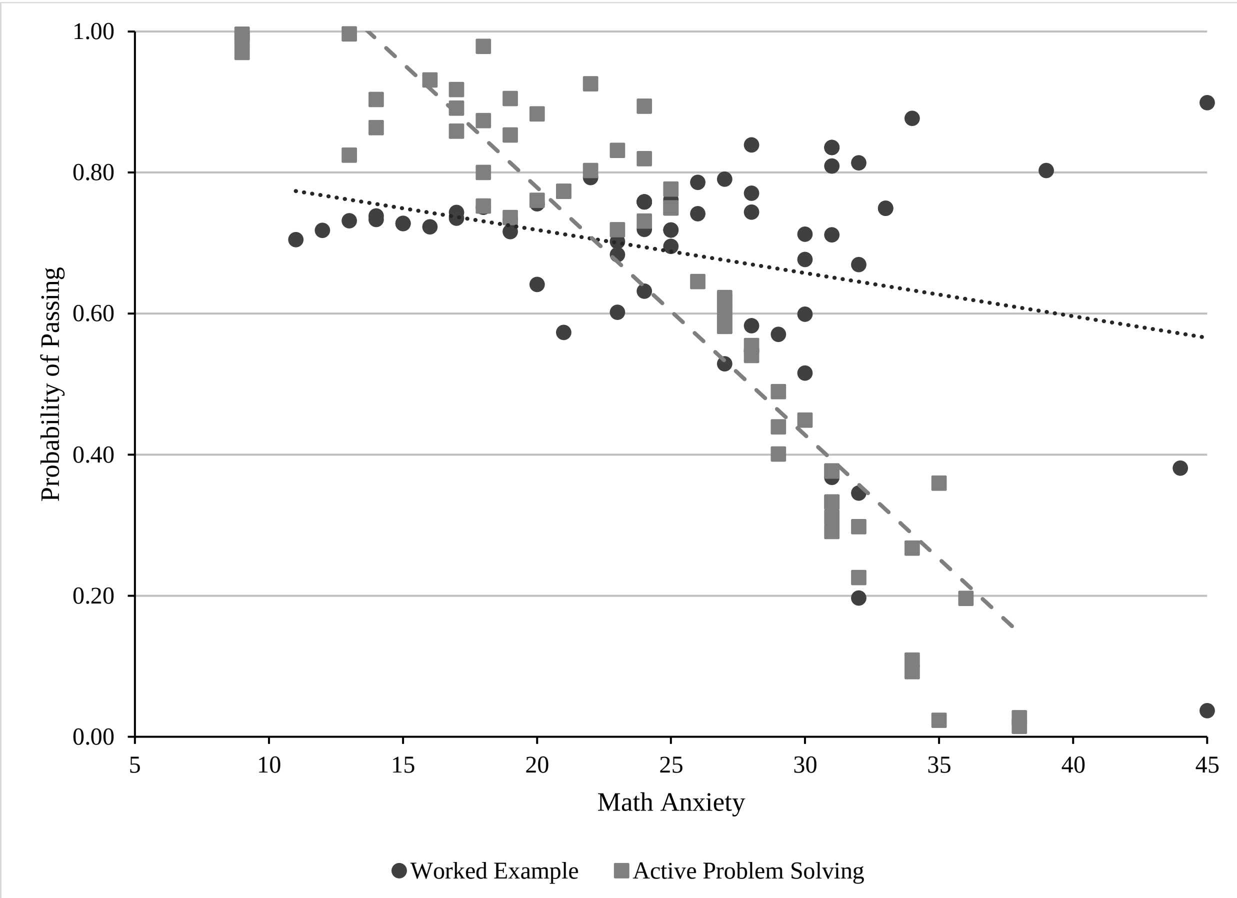
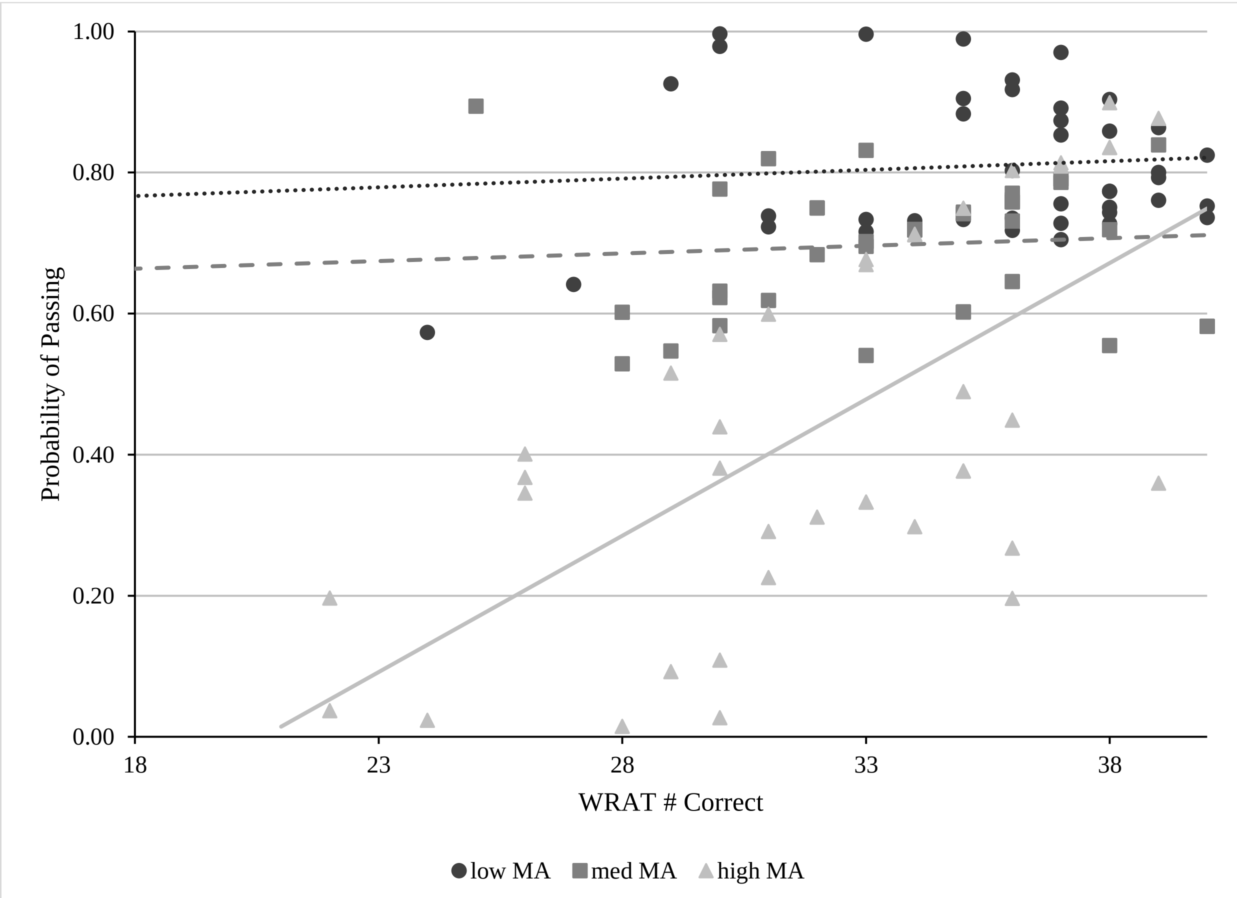
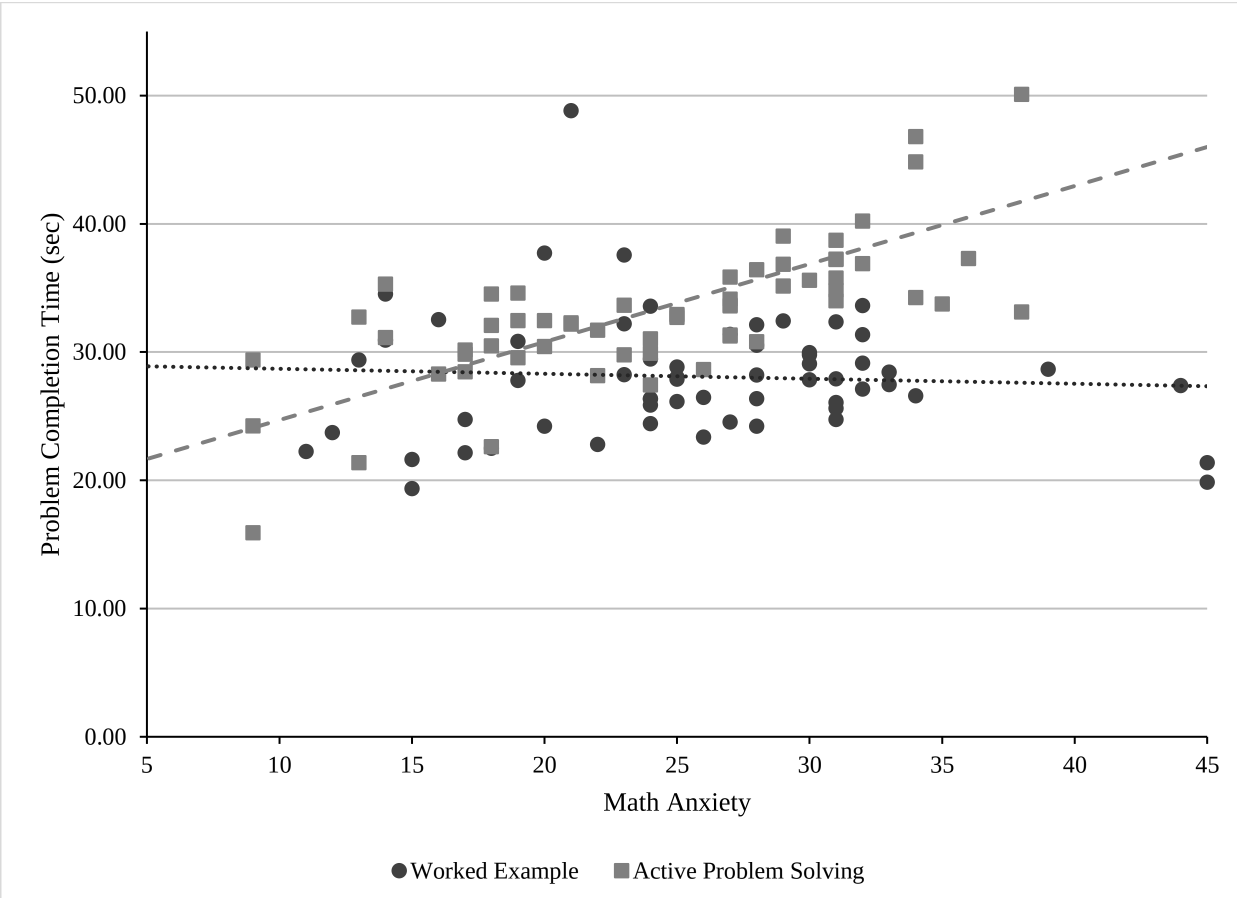


Figure 3.6 Probability of Passing by Math Skill and Math Anxiety for Worked Example and Active Problem-Solving Groups



A similar linear regression model was run but with problem completion time as the outcome variable and number correct added as a covariate. The full model was significant $F(8,112) = 2.05$, $p < 0.05$, $r^2 = 0.13$. The study conditionXmath anxiety interaction was significant, $\beta = 0.19$, $t(112) = 1.99$, $p < 0.05$. Those with higher math anxiety were slower to complete problems in the active problem-solving group than in the worked example group, see Figure 3.7. In addition, the three way interaction study conditionXmath anxietyXmath skill was significant, $\beta = -0.24$, $t(112) = -2.32$, $p < 0.05$. No other predictors were significant.

Figure 3.7 Problem Completion Time by Math Anxiety and Study Condition (Worked Example and Active Problem-Solving)



Worked Example Versus Faded Examples

To explore whether studying using either worked examples or faded examples lead to different learning outcomes along with math anxiety and math skill, I ran a linear regression model including study condition (WE vs Faded), math anxiety, math skill, and all interactions. The full model was significant $F(7,111) = 2.85$, $p < 0.01$, $r^2 = 0.15$, see Table 3.8. Only math skill predicted performance, $\beta = 0.26$, $t(111) = 2.57$, $p < 0.05$, with higher math skill being associated with higher performance. None of the other predictors were significant. I also ran the model including only those who reported they had never learned base number conversion. The full model was significant $F(7,102) = 3.12$, $p < 0.01$, $r^2 = 0.18$, but none of the predictors were significant. For the logistic regression, the full model was not significant, χ^2 (7) = 10.38, p > 0.05, Cox & Snell R^2 = 0.08, and none of the predictors were significant.

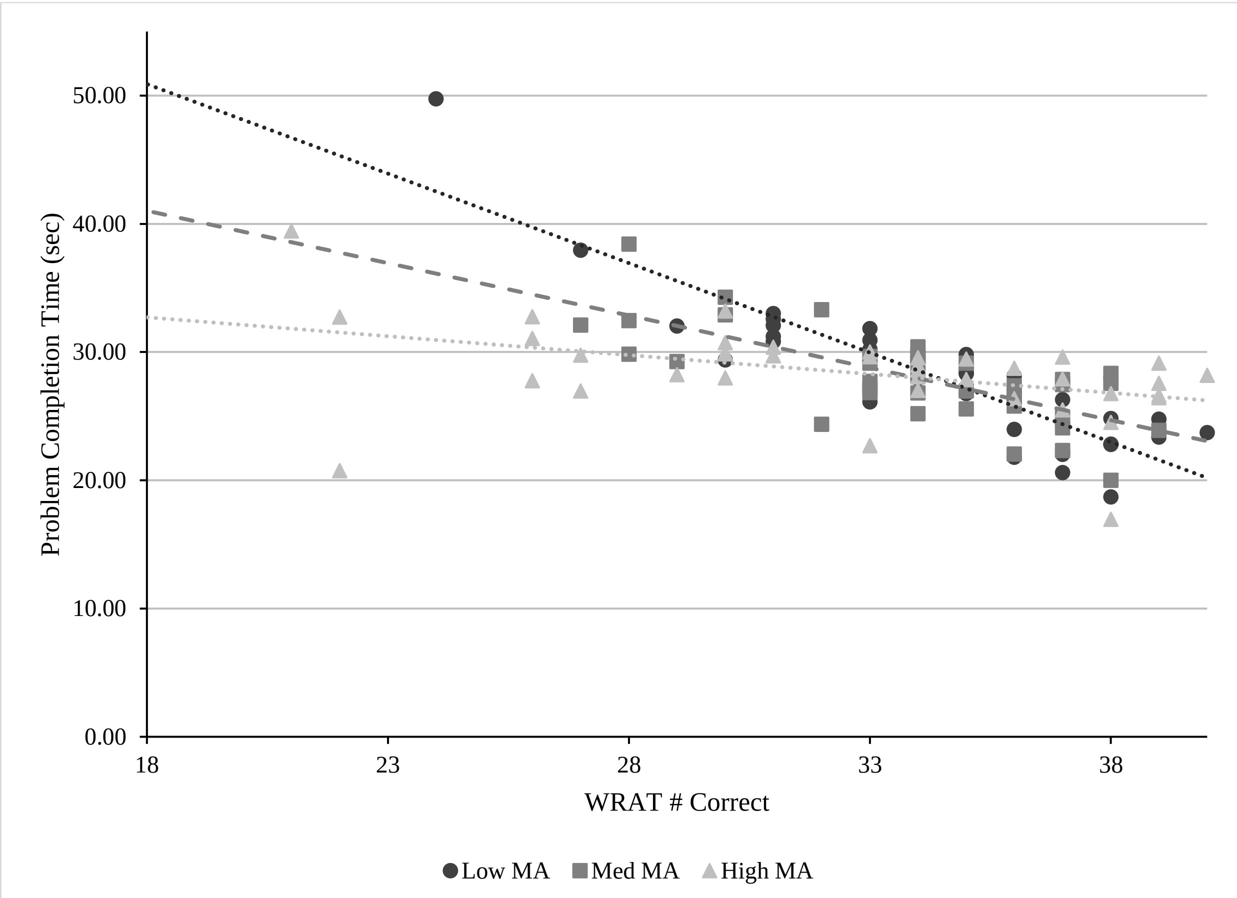
Table 3.8 Linear Regression Values for Worked Example and Faded Example Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	β	*t*	*P*
Study Condition	-0.26	0.57	-0.04	-0.45	0.65
Math Anxiety	-0.05	0.04	-0.13	-1.40	0.16
Math Skill	0.20	0.08	0.26	2.57	0.01*
Math SkillXMath Anxiety	0.01	0.01	0.11	1.11	0.27
Study CondXMath Anxiety	-0.01	0.08	-0.01	-0.10	0.92
Study CondXMath Skill	-0.13	0.16	-0.09	-0.84	0.40
Study CondXMath AnxietyXMath Skill	0.00	0.02	0.02	0.22	0.82

+ < 0.08, *<0.05, **<0.01, ***< 0.001

A similar linear regression model was run but with problem completion time as the outcome variable and number correct added as a covariate. The full model was significant $F(8,110) = 1.95$, $p = 0.06$, $r^2 = 0.12$. Math skill significantly predicted problem completion time, β = -0.35, $t(110) = -3.26$, $p < 0.01$, with higher math skill associated with faster problem completion time. Number correct on the final test was also marginally predictive of problem completion time, β = 0.18, $t(110) = 1.88$, $p = 0.06$, with greater number correct associated with slower problem completion time. In addition, the math anxietyXmath skill interaction was significant β = 0.21, $t(110) = 2.06$, $p < 0.05$. Individuals with high math anxiety and lower math skill tended to have faster problem completion times than those with medium or low math anxiety, but those with low math anxiety and higher math skill had faster problem completion time than those with medium or high math anxiety, see Figure 3.8. No other predictors were significant.

Figure 3.8 Problem Completion Time by Math Anxiety and Math Skill (Worked Example and Active Problem-Solving)



Active Problem Solving Versus Example Only

To explore whether studying using active problem solving versus examples only lead to different learning outcomes along with math anxiety and math skill, I ran a linear regression model including study condition (active problem solving versus example only), math anxiety, math skill, and all interactions. The full model was significant $F(7,104) = 4.10$, $p = 0.001$, $r^2 = 0.22$, see Table 3.9. Only math anxiety and math skill were significant predictors, $\beta = -0.30$, $t(104) = -3.21$, $p < 0.01$ and $\beta = 0.21$, $t(104) = 2.27$, $p < 0.05$ respectively. Math anxiety was associated with lower test performance and math skill was associated with higher test performance. No other predictors were significant. I also ran the model including only those who reported they had never learned base number conversion. The full model was significant $F(7,100) = 3.95$, $p = 0.001$, $r^2 = 0.22$. Math anxiety and math skill were still significant predictors.

Table 3.9 Linear Regression Values for Active Problem-Solving and Example Only Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Β	*t*	*P*
Study Condition	0.30	0.57	0.05	0.52	0.60
Math Anxiety	-0.13	0.04	-0.30	-3.21	0.002**
Math Skill	0.15	0.07	0.21	2.27	0.025*
Math SkillXMath Anxiety	0.01	0.01	0.09	0.96	0.34
Study CondXMath Anxiety	0.12	0.08	0.14	1.49	0.14
Study CondXMath Skill	0.19	0.13	0.13	1.42	0.16
Study CondXMath AnxietyXMath Skill	-0.02	0.02	-0.07	-0.80	0.43

+ < 0.08, *<0.05, **<0.01, ***< 0.001

For the logistic regression, the full model was significant, χ^2 (7) = 37.23, $p < 0.001$, Cox & Snell $R^2 = 0.28$, see Table 3.10. Math anxiety was a significant predictor of passing the immediate test, Exp(B) = 0.84, $p = 0.001$, 95% CI [0.76,0.93], with higher math anxiety associated with lower likelihood of passing the final test. In addition, the study conditionXmath skill interaction was significant, Exp(B) = 1.36, $p < 0.05$, 95% CI [1.04,1.76]. Individuals with higher math skill were more likely to pass in the examples only group than in the active problem-solving group, but the opposite occurred for those with lower math skills, see Figure 3.9. Also, the study conditionXmath anxiety interaction was marginal Exp(B) = 1.21, $p = 0.06$, 95% CI [0.99,1.47]. Individuals with higher math anxiety were less likely to pass the final test if in the example only group than in the active problem-solving group, see Figure 3.10. No other predictors were significant.

Table 3.10 Logistic Regression Values for Active Problem-Solving and Examples Only Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B)*
Study Condition	-0.06	0.56	0.01	0.92	0.95	[0.32,2.83]
Math Anxiety	-0.17	0.05	12.11	0.001	0.84	[0.76,0.93]**
Math Skill	0.08	0.07	1.40	0.24	1.08	[0.95,1.23]
Math SkillXMath Anxiety	0.01	0.01	1.02	0.31	1.01	[0.99,1.04]
Study CondXMath Anxiety	0.19	0.10	3.56	0.06	1.21	[0.99,1.47]+
Study CondXMath Skill	0.31	0.13	5.22	0.02	1.36	[1.04,1.76]*
Study CondXMath AnxietyXMath Skill	-0.03	0.02	1.89	0.17	0.97	[0.92,1.01]

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Figure 3.9 Probability of Passing by Math Skill and Study Condition (Active Problem-Solving versus Examples Only)

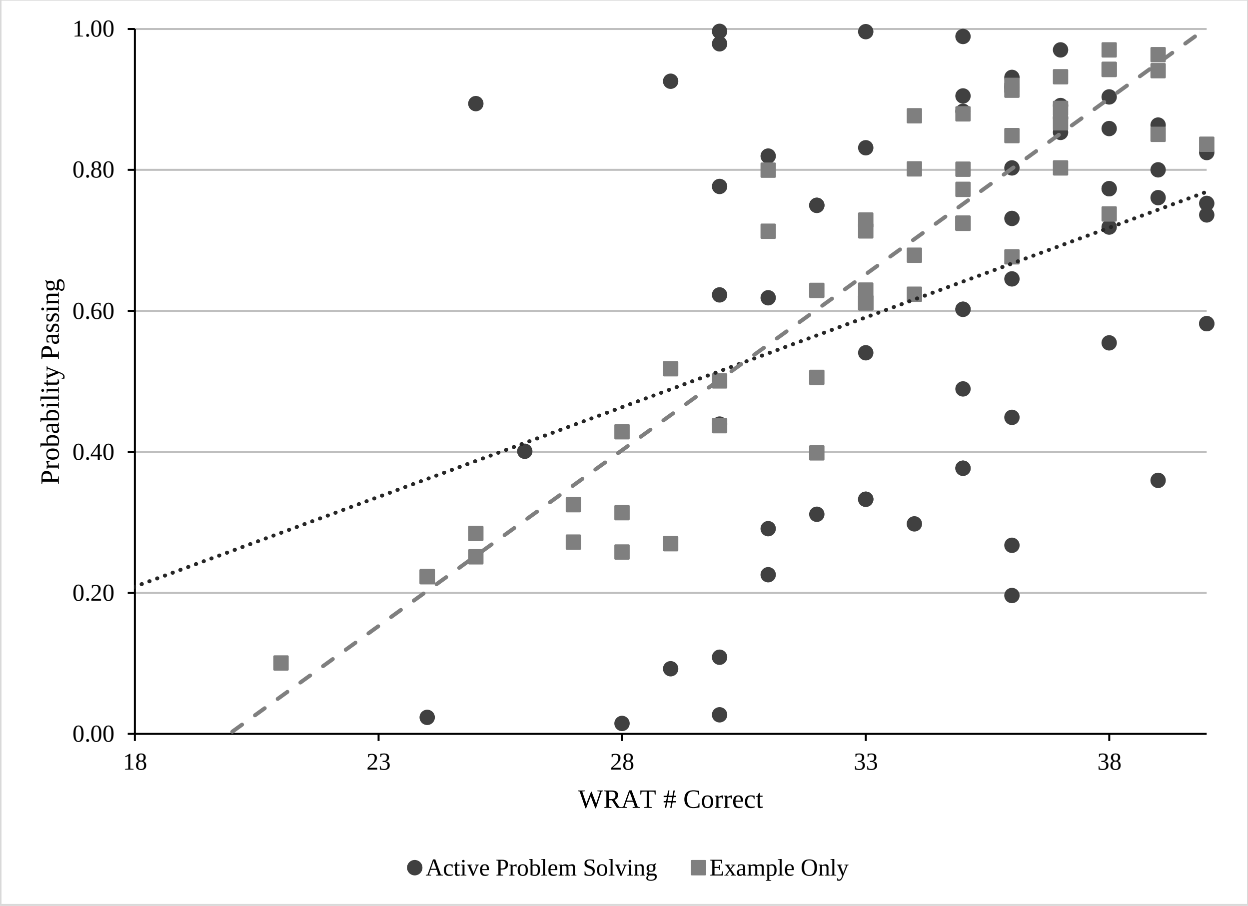
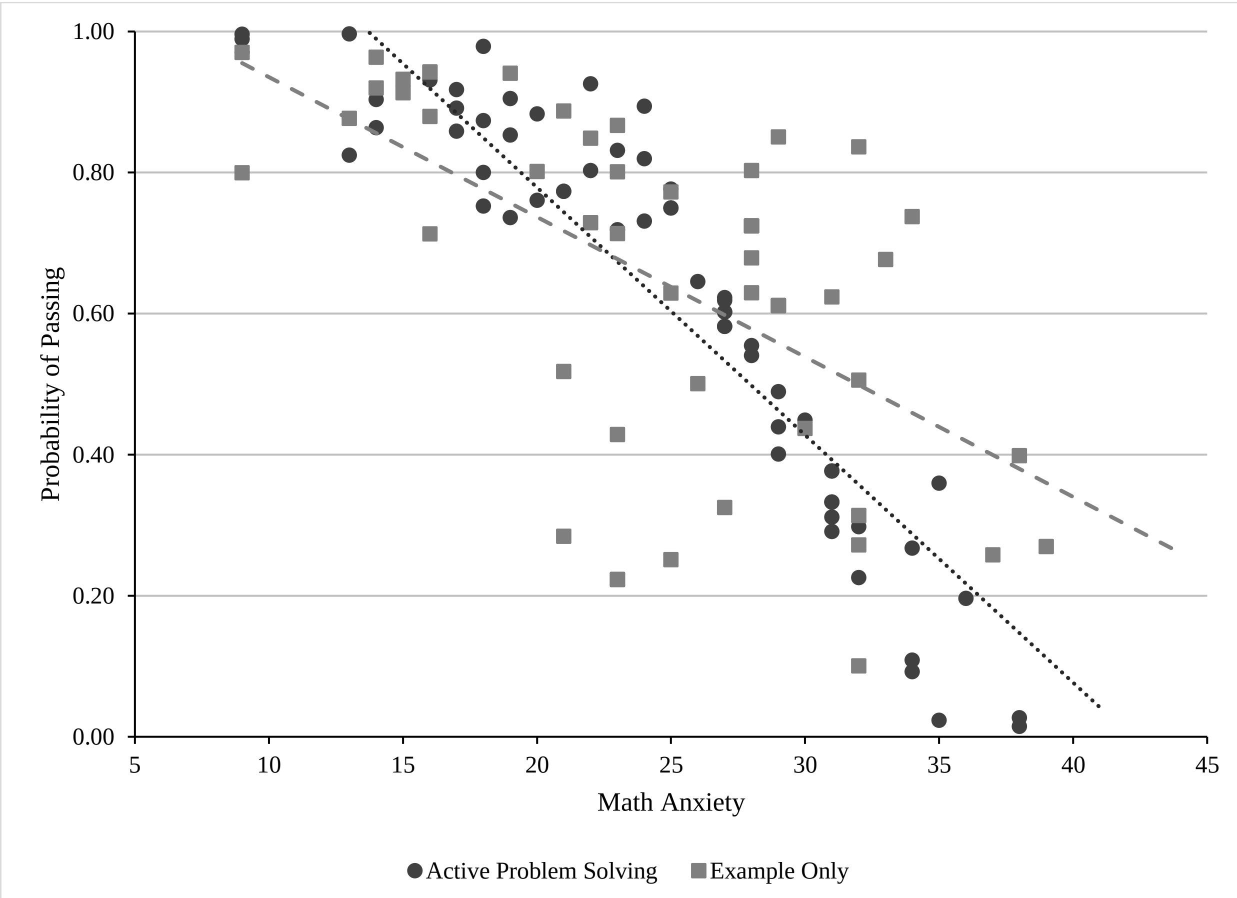
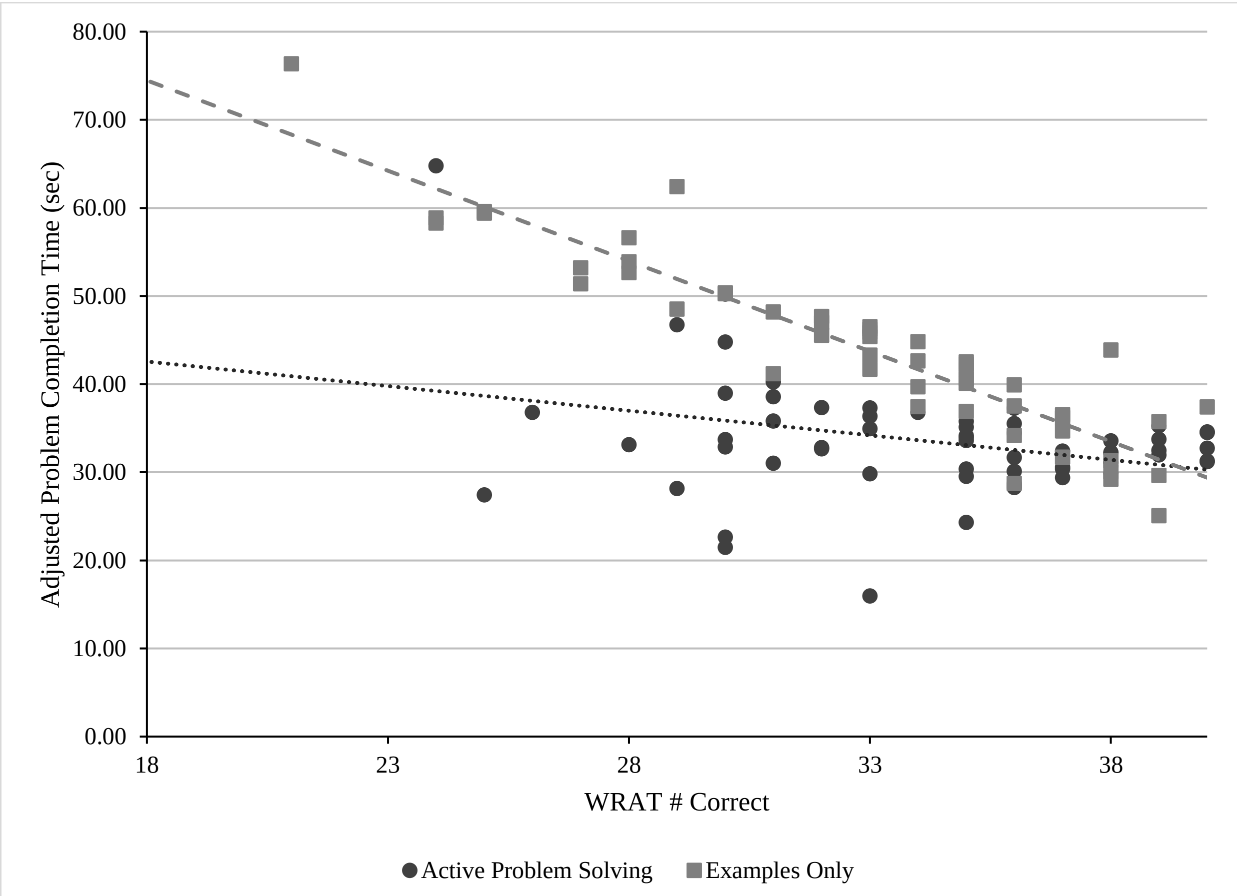


Figure 3.10 Probability of Passing by Math Anxiety and Study Condition (Active Problem-Solving versus Examples Only)



A similar linear regression model was run but with problem completion time as the outcome variable and number correct added as a covariate. The full model was significant $F(8,103) = 3.03$, $p < 0.01$, $r^2 = 0.19$. Study condition was significant, $\beta = 0.25$, $t(103) = 2.56$, $p < 0.05$, with individuals being faster in the active problem-solving group ($M = 33.51$, SE = 2.63) than in the examples only group ($M = 43.45$, $SE = 2.81$). Math anxiety was also significant $\beta = 0.21$, $t(103) = 2.56$, $p < 0.05$, with higher math anxiety associated with slower problem completion time. Math skill was marginal, $\beta = -0.18$, $t(103) = -1.86$, $p = 0.07$, with higher math skill associated with faster problem completion time. In addition, the study conditionXmath skill interaction was marginal, $\beta = -0.18$, $t(103) = -1.91$, $p = 0.06$. Individuals with lower math skill had longer problem completion times in the examples only group than in the active problem-solving group, see Figure 3.11. No other predictors were significant.

Figure 3.11 Adjusted Problem Completion Time by Math Skill and Study Condition (Active Problem-Solving versus Examples Only)



Worked Example Versus Example Only

To explore whether studying using worked examples versus example only lead to different learning outcomes along with math anxiety and math skill, I ran a linear regression model including study condition (worked example versus example only), math anxiety, math skill, and all interactions. The full model was significant $F(7,103) = 3.40$, $p < 0.01$, $r^2 = 0.19$, see Table 3.11. Only math skill was a significant predictor $\beta = 0.35$, $t(103) = 3.66$, $p < 0.001$, with higher math skill associated with higher test performance. No other predictors were significant. I also ran the model including only those who reported they had never learned base number conversion before. The full model was significant $F(7,99) = 3.23$, $p < 0.01$, $r^2 = 0.19$. Again, only math skill was significant.

Table 3.11 Linear Regression Values for Worked Example and Example Only Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Β	*t*	*P*
Study Condition	-0.12	0.59	-0.02	-0.20	0.84
Math Anxiety	-0.06	0.04	-0.14	-1.45	0.15
Math Skill	0.26	0.07	0.35	3.66	0.00***
Math SkillXMath Anxiety	0.00	0.01	0.05	0.49	0.62
Study CondXMath Anxiety	-0.02	0.08	-0.02	-0.23	0.82
Study CondXMath Skill	-0.02	0.14	-0.02	-0.15	0.88
Study CondXMath AnxietyXMath Skill	-0.01	0.02	-0.03	-0.31	0.75

+ < 0.08, *<0.05, **<0.01, ***< 0.001

For the logistic regression, the full model was significant, χ^2 (7) = 20.62, $p < 0.01$, Cox & Snell $R^2 = 0.17$, see Table 3.12. Math skill was the only significant predictor of passing the immediate test, Exp(B) = 1.19, $p = 0.01$, 95% CI [1.06,1.33], with higher math skill associated with a higher likelihood of passing the final test. No other predictors were significant.

Table 3.12 Logistic Regression Values for Worked Example and Example Only Groups Predicting Base Number Conversion Performance

Source	*B*	*SE B*	Wald χ^2	*p*	*Exp*(*B*)	*95% CI Exp*(*B*)
Study Condition	0.01	0.48	0.00	0.98	1.01	[0.40,2.57]
Math Anxiety	-0.04	0.04	1.59	0.21	0.96	[0.89,1.03]
Math Skill	0.17	0.06	8.91	0.003	1.19	[1.06,1.33]**
Math SkillXMath Anxiety	0.00	0.01	0.16	0.69	1.00	[0.99,1.02]
Study CondXMath Anxiety	-0.07	0.07	0.99	0.32	0.93	[0.81,1.07]
Study CondXMath Skill	0.12	0.12	1.07	0.30	1.13	[0.90,1.41]
Study CondXMath AnxietyXMath Skill	-0.02	0.02	0.79	0.38	0.98	[0.95,1.02]

+ < 0.08, *<0.05, **<0.01, ***< 0.001

A similar linear regression model was run but with problem completion time as the outcome variable and number correct added as a covariate. The full model was significant

$F(8,102) = 7.03$, $p < 0.001$, $r^2 = 0.36$. Study condition was significant, $\beta = 0.40$, $t(102) = 4.88$, $p < 0.001$, where individuals in the worked example group performed significantly faster ($M = 28.06$, $SE = 1.42$) than those in the example only group ($M = 43.45$, $SE = 2.81$). Math skill was also significant $\beta = -0.38$, $t(102) = -4.13$, $p < 0.001$, with higher math anxiety associated with slower problem completion time. No other predictors were significant.

General Discussion

Overall, we again found that both math anxiety and math skill were significant predictors of base number conversion performance. With higher math anxiety associated with lower performance on the immediate base number conversion test, and higher math skill associated with higher performance on the immediate base number conversion test. There was also a marginal math anxiety by math skill interaction, such that individuals with high math anxiety and low math skill tended to perform much worse than their low or medium anxious counterparts. We also found that when comparing the active problem-solving group to the worked example group, that individuals with high math anxiety tended to fare worse in the worked example group than in the active problem-solving group. Which is not in line with our previous finding from study 1.

When comparing the faded example to the worked example group, there were no notable differences between the two groups in learning outcomes or problem completion time. However, there were other effects found in this subsample, most notably there was a math anxiety by math skill interaction where individuals with high math anxiety and low math skill tended to have faster problem completion times than those with medium or low math anxiety. Possibly suggesting evidence of a speed-accuracy tradeoff. When comparing the active problem-solving group to the example only group there was some evidence of interplay between the study strategies and individual differences characteristics. Generally, being in the example only group was detrimental to the performance of individuals with high math anxiety and those with low math skill, compared to those in the active problem-solving group. I also found that individuals in the active problem-solving condition had faster problem completion times than those in the example only condition, and that individuals with lower math skills had longer problem completion times in the examples only group than their counterparts in the active problem-solving group. When comparing the worked example group to the example only group, we did not see any notable differences to learning outcomes but there were some differences in problem completion time. Individuals in the worked example group had faster problem completion times than those in the example only group. It is possible that some outliers could have influenced the problem completion times findings, but on closer examination I did not find more than a handful of outliers (above three standard deviations) and even then, only one individual had an unusually high average time around two minutes. It is difficult to understand what problem completion times really convey since they are such lengthy periods of time (around a minute) compared to traditional reaction times (on the order of seconds). Problem completion times reflect more than just the amount of time I takes to finish a problem, but also if the individual is checking their work or second guessing their answer. Due to the uncertainty of what problem completion times represent we decided not to look too far into them.

Replication of Study 1 Findings

Math anxiety and learning. In the current study we successfully replicated our math anxiety finding from study 1 and study 2, confirming that math anxiety is associated with difficulties on novel material above and beyond individual math skill. As discussed in the previous chapter, such difficulties with new material could be due to the underlying cognitive interference associated with high math anxiety, such as burdened working memory resources and/or difficulties in attentional control. Unfortunately, the current study does not allow for us to specifically explore the reasons why individuals with high math anxiety seem be less likely in mastering new math material. However, the task affect questionnaire completed by a subset of the sample sheds some light on what might be going on. As presented in Table 3.3, higher math anxiety was significantly associated with more anxiety during the base number conversion task and a greater frequency of off-task thoughts during the video, examples, and problem solving. Individuals with higher math anxiety reported having more off-task thoughts due to nervousness about performance and due to their own negative feelings towards math than their counterparts with lower math anxiety. These results indicate that individuals with high math anxiety were more likely to be distracted during both the learning and testing phase of the procedure. Making it more likely that they did not process the new information successfully and more likely to make errors during the problem-solving portion of the task. Given that this evidence is only correlational, it does not provide us with any direct evidence as to why math anxiety is associated with greater difficulty in master new mathematical content. To really assess what might be occurring, future studies should use other methodologies to better understand how individuals with high math anxiety are interacting with new math material.

Study strategies and learning. In study 1 we found that individuals with low skill in the worked example condition were less likely to pass the immediate base number conversion test than their counterparts in the active problem-solving condition. In contrast to our previous finding, in the current study we found that individuals with high math anxiety fared better on the immediate base number conversion test in the worked example group than in the active problem-solving group. There are three main differences between the worked example group in study 1 and that in the current study. First, in study 1 participants in the worked example group were presented with either three or four worked examples interleaved with either two or three practice problems depending on the sub-sample, in contrast, participants in study 3 (the current study) were presented with five worked examples and three practice problems. Second, the order of the worked examples was different; in study 1, worked examples were interleaved with practice problems, whereas in study 3, worked examples were presented in a block followed by the practice problems (to align with the order of the faded example condition). Third, study 3 included one example and one practice problem of a more difficult base number conversion problem while individuals in the active practice group were never presented with an example of the more difficult problem type.

Taking a closer look at which test problems individuals in the worked example group were getting correct, it does not seem that the third difference between the studies would account for the contrasting findings between study 1 and study 3. Individuals with high math anxiety in the worked example group's higher rates of success were not accounted for by getting the more difficult base number conversion problems correct, but that they were getting more of the standard problems correct than their counterparts in the active problem-solving group. In addition, it does not seem likely that the addition of one/two extra worked examples or one extra practice problem would account for such a difference, but it is not possible to know for sure without a controlled study assessing the effects of different numbers of examples and practice problems.

It is possible that the change in example/problem order could have made a difference in performance, although it would be at odds with the literature on effective worked examples. Presenting the worked examples blocked in study 3 might have helped individuals with high math anxiety compare and contrast between different examples, facilitating their representation of the procedure. This would be surprising because generally, worked examples are thought to be most effective when presented in close proximity to a practice problem (Atkinson et al., 2000). Also, the long-term memory literature suggests that interleaving is generally more effective for learning, even math learning (Rohrer & Taylor, 2006), but this finding is more so with regards to studying different types of problems interleaved versus blocked (Rohrer & Pashler, 2010). Again, the only way to really determine the reason for the discrepant findings it to systematically assess the impact of different problem orderings.

Currently, it is difficult to understand what might account for the discrepant findings. Therefore, it is unclear how worked examples versus active problem-solving impact learning for individuals with high math anxiety or low math skill. It is possible that there is too much variability in the way individuals approach studying worked examples, such that different individuals could approach studying the examples in very different ways. It might be more informative to look at component behaviors involved in studying worked examples versus completing practice problems. Taking a more fine-grained look at the actual behaviors individuals (e.g. using a think-aloud protocol) are exhibiting during study might lead to more consistent results with regards to learning outcomes.

Faded Examples and Learning

I had originally thought that the faded example group would perform better than the worked example group due to the gradual transition from examples to practice problems. Faded examples were more engaging than worked examples and encourage individuals to focus on the various steps of the procedure one at a time. However, we did not find any overall differences in learning outcomes between the two groups in accuracy or problem completion time. We need to consider that most people generally did fairly well on the standard set of base number conversion problems, while very few individuals in either condition successfully completed the two more difficult base number conversion problems. It is possible that since the standard task was rather easy for most participants, and the difficult problems seem to have been too difficult, that we simply do not have the appropriate task to assess differences in learning outcomes between the strategies. This same argument also applies for our inconsistent findings in the effects of worked examples versus active problem-solving discussed above. It is also possible that the overall benefits of faded example versus worked examples are not that large, but the only way to assess if this is the case would be to alter the materials to allow for more variance in outcomes.

Examples Only and Learning

I originally hypothesized that the example only condition would be detrimental to learning especially for individuals with high math anxiety or low math skill than the worked example or active problem-solving conditions. My hypothesis was partially supported with individuals with high math anxiety or low math skill having worse learning outcomes in the example only group than in the active problem-solving group. However, when comparing to the worked example group, there were no notable differences in accuracy, but some notable differences in completion times, with individuals performing faster in the worked example than in the example only group. These findings suggest that having the opportunity to practice newly learned mathematical procedures is vital to learning and achieving fluency with new material for individuals with high math anxiety or low math skill. This finding is consistent with the testing literature, such that tests as a study strategy seem to lead to better learning outcomes than does simply re-reading (for a meta-analysis see Rowland, 2014). Some hypothesized reasons that testing is thought to enhance learning is by increasing retrieval strength (the more you recall something the easier it becomes to recall it at a later time) or it could simply involve deeper processing. However, in our study the benefit of testing (as presented in the active problem-solving condition) did not influence everyone. It seems that for a relatively straightforward algorithm such as base number conversions, studying a set of examples was fairly effective for individuals with low math anxiety or with high math skill, but it was not sufficient for individuals with high math anxiety or low math skill. Again, if we had a task that was a little more challenging we might have been able to see greater differences in learning outcomes.

Conclusions

In summary, we found additional evidence as to the negative effect of math anxiety on learning new math material, mixed evidence on the effects of worked examples versus active problem solving as strategies for individuals with high math anxiety or low math skill, no evidence of the benefit of faded over worked examples, and evidence for the benefit of active problem solving over studying only examples during learning. These findings shed some more light on the intricate interplay between math anxiety, math skill, study strategies and their influence on learning new math material. However, the relative benefits of specific study strategies for individuals with high math anxiety or low math skill still remain unclear, with the exception of the benefit of problem-solving versus studying only examples. The task we used is still too easy for our high math achieving sample. The benefits of different study strategies will likely be more apparent in a task with more variability in performance. We do however have fairly robust evidence as to the negative influence of math anxiety on learning of new material, which future studies need to explore further.

CHAPTER IV

Math Anxiety and Student Study Habits

In previous chapters, I have focused on assessing the influence of math anxiety on learning of new math material and exploring the potential benefits of some study strategies over others for learning. In the current chapter, my focus is to explore if students' actual use of study strategies in quantitative courses relates to their math anxiety. Only one study, to my knowledge, currently provides any evidence as to the possible differences in study habits between individuals with high and low math anxiety. Bessant (1995) found that higher math anxiety was associated with a higher orientation towards using rote memorization (e.g. rehearsal) for learning. Although informative, their measure of study strategies did not assess student utilization of specific study strategies that previous research has found to be effective for supporting learning.

Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013) compiled the most promising evidence-based strategies for enhancing student learning known in cognitive and educational psychology. They concluded that practice testing and distributed practice had high utility for their benefits extend to a wide variety of contexts, while elaborative interrogation ["generating an explanation for why an explicitly stated fact or concept is true," (Dunlosky et al., 2013, p. 6)], self-explanation, and interleaved practice had moderate utility since they generalize to some contexts, but the evidence is more limited for these techniques. They found that five techniques were not strongly/consistently associated with benefits to performance: summarization, highlighting, keyword mnemonic, imagery use for text learning, and rereading. The Dunlosky et al. (2013) monograph provides us with a general idea for what specific study strategies are generally effective for learning versus those that are not. Not all strategies found to be beneficial have been explicitly tested in mathematics, with the exception of testing (van Gog & Kester, 2012), spacing (Rohrer & Taylor, 2006), self-explanation (Atkinson, Renkl, & Merrill, 2003; Rittle-Johnson, 2006; Rittle-Johnson, Loehr, & Durkin, 2017), and interleaving (Rohrer & Taylor, 2007). Although self-explanation, spacing, and interleaving have been found to have positive effects for learning outcomes for math content, van Gog & Kester (2012) did not find a benefit of testing over restudy of examples for math problems which is in line with the vast majority of the research on the benefits of studying worked examples over completing practice problems (Sweller & Cooper, 1985; Cooper & Sweller, 1987). Overall, the evidence as to the direct effectiveness for most of the discussed evidence-based study strategies, for math learning specifically, is rather limited.

The current study was not focused on the effectiveness of the study strategies used but more so to assess if individuals with high math anxiety tend to have different study habits than their less anxious peers. While looking for measures that specifically assessed the study strategies known to be effective, specifically those discussed in Dunlosky et al. (2013), I did not find any previously existing reliable and valid scales that assessed a substantial number of the strategies mentioned above. The closest measure I found was the revised Motivated Strategies for Learning Questionnaire (MSLQ) used in Berger and Karabenick (2011), which was adapted from Duncan and McKeachie (2005). The MSLQ assesses both motivation and learning strategy use through a set of subscales assessing individuals' use of cognitive, metacognitive, and resource management strategies as well as their values and expectancies within a domain. Berger and Karabenick (2011) used their adapted measure to assess the relationship between motivation and study strategies in math courses for 9^{th} grade students. They found that student self-efficacy at the beginning of the term positively predicted students' future use of elaboration (connecting new information to content from other courses or previous knowledge), metacognition (planning, monitoring, and regulation), and time/study management by the end of the term in their math courses, while cost and value perceptions of math positively predicted use of rehearsal as a study strategy.

For the current study, we created an online questionnaire to assess student's reported study strategies for math courses and well as their math anxiety. To be eligible students had to had completed a quantitative course within the last year. Within the survey, individuals completed the revised MSLQ learning strategies subscales (Berger & Karabenick, 2013), two additional study habit measures we created to assess their use of cognitive strategies (spacing, testing, and interleaving) and specific math study strategies (e.g. studying examples versus completing practice problems), math anxiety, and measures of basic math skill. I hypothesize that we will find that individuals with math anxiety will be more likely to report using reading, and less likely to report using elaboration, metacognition, and time/study management.

Methods

Participants

390 University of Michigan students volunteered to participate in the online survey. Of those, 37 were not eligible for they did not take a quantitative course within the last 12 months, and an additional 5 were younger than 18 years of age. Of the remaining 348, 293 had complete data and were used in all of the following analyses. 36 of those with incomplete data had reported math anxiety; those with incomplete data (M = 28.14, SE = 1.00) did not significantly differ from those with complete data (M = 26.30, SE = 0.37) on math anxiety, $t(45.29) = 1.73$, p

> 0.05. Of those with incomplete data, most exited the survey early during the questionnaire portion, on average they completed 24.64% (*SE* = 3.88) of the survey before exiting.

Of the 293 with complete data, 106 (36.2%) were male and the average age was 19.03 years (*SE* = 0.09). 76.5% of the sample were either freshman or sophomores in college, while the remaining 26.5% were further along. 8.2% reported as being Spanish, Hispanic, or Latinx, 67.9% as white, 7.8% as black, 1.4% as American Indian or Alaska Native, 25.6% as Asian, 0.3% as Native Hawaiian or Pacific Islander; 4.8% reported as other most of whom identified as middle eastern (note: race/ethnicity categories not mutually exclusive some people indicated more than one race/ethnicity). Most of the sample reported a family annual income of greater than $100,000, 58.7%. 35.5% of the sample were social science majors, 34.8% were science, technology, engineering, or mathematics majors, 17.7% were business, economics, or finance majors, and 11.9% were humanities, arts, or undecided.

Procedures

The survey was conducted using the online platform Qualtrics and completed remotely from participants' personal computers. Participants were recruited either through an ad in the psychology department newsletter, emails sent to quantitative course instructors, or through the psychology subject pool for credit. Subjects recruited through the newsletter or course emails were entered into a lottery for a chance to win a $100 amazon gift card, for which their odds were approximately 1 in 100. The survey consisted of four main sections presented in the following order: consent and eligibility, math anxiety and study habits questionnaires, basic math skills measures, and demographics.

Materials

Consent and eligibility. Participants were informed that they were volunteering to complete a brief 15 to 30-minute survey on their feelings and attitudes towards math as well as their study habits, according to IRB guidelines. They were informed that upon completing the survey they would be entered to win a $100 amazon gift card per 100 persons participating or that they would receive course credit (depending on whether they were recruited for pay or through the psychology subject pool). Before asked to consent, they were asked if they had taken a quantitative course in the last 12 months and if they were 18 years of age or older. If they responded no to either question, they were not eligible and the program would immediately take them to the end of the survey. If they responded yes to both questions they were asked if they consented to participate in the survey.

Math anxiety and study habits questionnaires.

Math anxiety. To measure math anxiety, I used the abbreviated Mathematics Anxiety Scale (AMAS). It is a short nine-item math anxiety questionnaire ($\alpha = 0.85$) adapted by Hopko and colleagues (2003) from the original 98 item Mathematics Anxiety Scale by Richardson & Suinn (1972). Participants were instructed to use a scale of 1 (not anxious at all) to 5 (very much anxious) to rate how anxious a given situation made them feel. For example, "Taking an examination in a math course."

Cognitive study strategies. I created a set of items that would assess students' use of the following cognitive study strategies: spacing versus massing, testing versus rereading, and interleaving versus blocking. Using a Likert-type five-point scale, participants were to indicate how true each statement was of themselves, with 1 being "not at all like me" and 5 being "very much like me". The following were the items presented:

- When I study math, I space out my study sessions over an extended period of time (e.g. days, weeks, etc.) [spacing]
- I study math by cramming the night before an exam or quiz. [massing]
- I study math by testing myself with new math problems or practice exams without looking at the solution. [testing]
- When I study math, I mostly reread my notes. [rereading]
- When I study math, I study one kind of problem first before moving on to a different kind of problem. [blocking]
- I study math by switching between different kinds of problems. [interleaving]

A factor analysis using Principal Axis Factoring with a Varimax rotation with Kaiser Normalization, revealed three factors. Factor 1 explained 34% of the variance and consisted of the spacing (0.60) and massing (-0.87) items. Factor 2 explained 14.73% of the variance and consisted of the blocking item (0.9). Factor 3 explained 13.08% of the variance and consisted of the interleaving item (0.61). However, the Cronbach's alpha for the spacing and massing items was low ($\alpha = 0.68$). Considering that none of the items really hung well together I decided to include each item as a separate variable in all the following analyses.

Specific study strategies. I also used a set of items that would get at students' specific study habits for their math courses. Participants were instructed to use a five-point Likert-type scale to rate how likely they were to use each of the following strategies, with 1 being "very likely" and 5 being "very unlikely":

- Study examples of solved problems that you had already completed for homework
- Study examples of solved problems that the instructor provided

- Copy and resolve problems that you have already solved but without looking at the solution
- Solve new problems that are similar to those that you have solved in the past (e.g. problems you didn't have to do for homework)
- Read notes, textbooks, or online textual resources
- Watch videos (e.g. Khan academy)
- Avoid studying
- Other

A factor analysis using Principal Axis Factoring with a Varimax rotation with Kaiser Normalization, revealed three factors. Factor 1 explained 35.28 % of the variance and consisted of the following items: study homework (0.75), study instructor examples (0.67), resolve old problems (0.51), and solve new similar problems (0.44). Factor 2 explained 14.45% of the variance and consisted of the avoid study (0.84) item. Factor 3 explained 12.55% of the variance and consisted of the reading notes, textbook or online resources (0.60) item. The Cronbach's alpha for the first factor was adequate ($\alpha = 0.71$). Since the first four items hung well together, I averaged them together for a composite score named 'resolve and study problems'. The remaining items are used as individual items. There was an error in the initial round of data collection for the items "Read notes, textbooks, or online textual resources," and "Watch videos (e.g. Khan academy)" which lead us to only have 257 responses to those items. Due to this, I decided to omit these items from the main analysis to maintain a larger sample size.

Math Specific Motivated Strategies for Learning Questionnaire (MSLQ). The math specific MSLQ is a 44-item survey that assesses student learning strategies and motivation for math (Berger & Karabenick, 2011). It is adapted from the well validated college version of the

MSLQ (Duncan & McKeachie, 2005). I only included the 33 learning strategies items which consisted of three main scales, that each consisted of two to three smaller sub-scales. The cognitive strategies scales consisted of the 4-item rehearsal subscale (e.g. "When I study math, I memorize what I need to learn by repeating it over and over to myself"), the 4-item organization sub-scale (e.g. "When I study math, I make outlines to organize what I have to learn"), and the 4-item elaboration sub-scale (e.g. "I connect what I learn in math to what I am learning in some other classes"). The metacognitive strategies scale consisted of the 5-item planning sub-scale (e.g. "I plan how I am going to study new math topics before I begin"), the 4-item monitoring sub-scale (e.g. "When I study math, I ask myself questions to make sure I know what I have been learning"), and the 4-item regulation sub-scale (e.g. "If I get confused with something I'm studying in math, I go back and try to figure it out"). The final scale assesses resource management and consists of the 4-item time and study environment subscale (e.g. "I make sure I have as few distractions as possible when I study math") and the 4-item help-seeking sub-scale (e.g. "If I don't understand something in math I ask my teacher for help"). For all items used please refer to Appendix 3.

Basic math skills measures. Participants completed four sets of math skills measures, A and B forms of the Woodcock Johnson III calculation subtest, and two additional sets of 28 simple arithmetic problems. The WJ III calculation subtest is a well validated, reliable, and normed measure that consists of 25 math problems that range in difficulty from single-digit arithmetic to arithmetic with fractions (test reliability = 0.86; McGrew, & Woodcock, 2001; Schrank, McGrew, & Woodcock, 2001). The additional simple arithmetic task consisted of 28 distinct, single-digit arithmetic problems (addition, subtraction, and multiplication), except for division problems which had one double-digit and one single-digit operand. Single digits ranged from 2-9 were used to construct all the addition, subtraction and multiplication problems, while the division problems were constructed based off of the multiplication problems. There were two forms of the simple arithmetic task, Form B was merely Form A but with all addition problems converted to division and all subtraction converted to multiplication.

One form of the WJ III calculation and one form of the arithmetic measure were presented together in a block under speed or accuracy instructions. Under speed instructions participants were instructed with the following, “For this group of problems, please GO AS FAST AS YOU CAN while being as accurate as possible.” The accuracy instructions stated the following, “For this group of problems, TAKE YOUR TIME and focus on being accurate.” Participants were presented with both sets of instructions, but some participants received the speed instructions first while others received the accuracy instructions first. Form A of the arithmetic problems and Form A of the WJ III were always presented as the first block. The effects of speed and accuracy instructions on individual performance is not in line with the aims of the current study but will be assessed in future analyses.

Demographics. Finally, participants reported their demographics and information regarding their last quantitative course. Participants were asked to report the last quantitative course taken, the grade they received in said course, their intended major, year of college, age, sex, race/ethnicity, and household income (including parent income for those under 24).

Results

Descriptives

The average math anxiety sum score of was 26.30 (SE = 0.37). Overall, the mean number correct of the WJ III was 23.72 out of 25 (SE = 0.09) and for the basic math task 27.40 of 28 (SE = 0.05). Most of the sample reported their last course was calculus I or higher (55.6%), followed by statistics (34.5%), precalculus or lower (6.1%), and 3.8% reported taking some other quantitative course. More than half the sample reported receiving between an A- to an A+ in their last quantitative course (55.6%), 35.6% reported between B- to a B+, and the remaining 8.8% had a C+ or lower. Women (M = 27.59, SE = 0.43) had higher math anxiety than men (M = 24.02, SE = 0.64), $t(198.83) = -4.65$, $p < 0.001$, but they did not significantly differ in age, grade in last quantitative course, or any of the math skills measures. See Table 4.1 for correlations between study strategies, math anxiety, quantitative grade, and math skills. Since grade in last quantitative course did not correlate with any of the study habits measures, I did not run any additional analyses assessing the relationship between study habits and course grade.

Table 4.1 Correlations between study strategies, math anxiety, quantitative course grade, and math skills.

	Math Anxiety	Quant Grade	Mean WJ	Mean Basic Math
Spacing	0.02	-0.10	-0.03	-0.06
Massing	0.15*	-0.00	-0.02	-0.01
Testing	0.01	-0.07	-0.05	-0.02
Reading	0.16**	-0.02	0.03	-0.04
Interleaving	0.06	-0.05	0.01	-0.01
Blocking	-0.02	0.04	0.02	0.06
Study Homework	-0.01	-0.02	-0.05	-0.0
Study Instructor Example	-0.01	0.01	-0.03	-0.1
Resolve Problems	-0.03	0.03	0.02	-0.02
Solve New	0.10	-0.03	-0.02	0.01
Read Materials (N = 257)	-0.07	-0.05	-0.03	-0.00
Watch Videos (N = 257)	-0.02	0.01	0.02	0.03
Avoid	-0.13*	-0.05	-0.00	0.10
Other	-0.12	0.06	0.00	0.07
Rehearsal	0.28**	0.01	0.04	-0.05
Organization	0.23**	0.08	0.06	-0.07
Elaboration	-0.28**	-0.11	0.07	0.00
Planning	-0.00	-0.02	-0.04	-0.15*
Monitoring	-0.13*	-0.14*	-0.07	-0.06
Regulation	-0.14*	-0.19**	0.01	-0.02
Help Seeking	-0.10	-0.09	0.06	0.02
Management	-0.00	-0.06	0.07	-0.02

+ < 0.08, *<0.05, **<0.01, ***< 0.001

Math Anxiety and Study Strategies

To determine if math anxiety is related to differences in study habits, I ran three sets of linear regressions with math anxiety as the dependent variable. Sex and grade in quantitative course were used as covariates in all three models. The first model included the cognitive strategies (spacing, massing, testing, reading, interleaving, and blocking) as the predictor variables. The full model was significant, $F(8,284) = 8.15$, $p < 0.001$, $r^2 = 0.19$. Sex and grade in quantitative course were both significant, $\beta = 0.27$, $t(284) = 5.03$, $p < 0.001$ and $\beta = 0.25$, $t(284) = 4.71$, $p < 0.001$ respectively. Women reported higher math anxiety than men, and higher math anxiety was associated with lower course grades. Overall, higher math anxiety was associated with greater use of spacing ($\beta = 0.16$, $t(284) = 2.42$, $p < 0.05$), massing ($\beta = 0.22$, $t(284) = 3.44$, $p = 0.001$), and reading ($\beta = 0.12$, $t(284) = 2.17$, $p < 0.05$) during study. See Table 4.2 for all values.

Table 4.2 Linear Regression Values Cognitive Strategies Predicting Math Anxiety

Source	*B*	*SE B*	β	*T*	*P*
Sex	3.58	0.71	0.27	5.03	0.00**
Quant Grade	0.92	0.19	0.35	4.71	0.00**
Spacing	0.93	0.38	0.16	2.42	0.02*
Massing	1.17	0.34	0.22	3.44	0.00**
Testing	0.17	0.32	0.03	0.53	0.60
Reading	0.65	0.30	0.12	2.17	0.03*
Blocking	-0.14	0.35	-0.03	-0.40	0.69
Interleaving	-0.18	0.32	-0.03	-0.56	0.57

+ < 0.08, *<0.05, **<0.01, ***< 0.001

The second model included the specific study strategies as predictors. The full model was significant, $F(5,287) = 10.13$, $p < 0.001$, $r^2 = 0.15$. Again, sex and quantitative grade were significant, see Table 4.3 for values. None of the specific study strategies were related to math anxiety, even when including the reading notes and watch videos items.

Table 4.3 Linear Regression Values Specific Study Strategies Predicting Math Anxiety

Source	*B*	*SE B*	Β	*T*	*p*
Sex	3.51	0.73	0.27	4.79	0.00**
Quant Grade	0.86	0.20	0.24	4.31	0.00**
Study/Resolve Problems	0.12	0.41	0.02	0.29	0.78
Avoid Study	-0.51	0.31	-0.10	-1.67	0.10
Other	-0.43	0.26	-0.10	-1.64	0.10

+ < 0.08, *<0.05, **<0.01, ***< 0.001

The third model included the MSLQ sub-scales as predictors. The full model was significant, $F(5,287) = 10.67$, $p < 0.001$, $r^2 = 0.28$. Once again, sex and grade in quant course were significant, see Table 4.4 for values. Higher math anxiety was associated with greater use of rehearsal ($\beta = 0.24$, $t(282) = 4.16$, $p < 0.001$) and organization ($\beta = 0.15$, $t(282) = 2.58$, $p < 0.05$). In addition, higher math anxiety was associated with less use of elaboration ($\beta = -0.24$, $t(282) = -4.05$, $p < 0.001$) and help seeking ($\beta = -0.14$, $t(282) = 2.49$, $p < 0.05$).

Table 4.4 Linear Regression Values MSLQ Learning Sub-Scales Predicting Math Anxiety

Source	*B*	*SE B*	β	*T*	*P*
Sex	2.24	0.71	0.17	3.17	0.00**
Quant Grade	0.64	0.19	0.18	3.39	0.00**
Rehearsal	0.43	0.10	0.24	4.16	0.00**
Organization	0.26	0.10	0.15	2.58	0.01*
Elaboration	-0.43	0.11	-0.24	-4.05	0.00**
Planning	0.07	0.08	0.05	0.83	0.41
Monitoring	-0.16	0.14	-0.08	-1.15	0.25
Regulation	0.08	0.14	0.04	0.62	0.54
Help Seeking	-0.30	0.12	-0.14	-2.49	0.01*
Management	-0.01	0.12	-0.01	-0.09	0.93

+ < 0.08, *<0.05, **<0.01, ***< 0.001

General Discussion

We found that higher math anxiety was more apparent in women and associated with lower grade in last quantitative course, increased use of spacing, massing, reading, rehearsal, and organization, and decreased use of elaboration and help-seeking. These findings mostly support my hypothesis, except for we did not find any differences in metacognitive strategy use based on math anxiety. It was interesting that high math anxiety was associated with increased use of both spacing and massing as study strategies. Since these are highly successful students (the vast majority of the sample received either an A or a B in their last quantitative course), they just likely spent more time studying all together, such that they studied frequently but also crammed before an exam. In hindsight, one thing we should have measured is total amount of time generally used for study during the week and before an exam to have a better understanding of how individuals with high math anxiety distribute their study time. It was surprising that individuals with math anxiety did not show any differences in their use of studying and resolving problems for study. I speculated that individuals with high math anxiety would spend more time studying old examples and less time solving new or old problems than their less anxious peers. However, the factor analysis revealed that overall most students tended to use both strategies in tandem. In the future, I would like to collect data on how individuals allocated their study time to reviewing examples versus solving or resolving problems. This might indicate some differences between individuals with high and low math anxiety.

Since none of the study strategies were associated with student grades and the study relied on retrospective reports up to a year after the last quantitative course was taken, it is not currently possible to determine whether the differences in strategy use between individuals with high or low math anxiety lead to different learning outcomes. In addition, we have little variability to detect differences in learning outcomes because this is a high performing sample. However, it does seem that individuals with higher math anxiety to tend use some "less effective" (as defined by the general cognitive and education literature in Dunlosky et al., 2013) study strategies more often than those with lower math anxiety (i.e. massing, rehearsal, and reading) and helpful learning strategies less often (i.e. elaboration). With regards to their use of organization more than their less anxious counterparts, it is currently not clear whether organization in general seen as greatly beneficial to learning outcomes. In addition, Dunlosky et al. (2013) did not specifically discuss the potential benefits of help-seeking behaviors, but just through intuition it does seem rather disadvantageous for individuals with high math anxiety to be less likely to seek help when struggling with material. It is possible that the differences between individuals with high math anxiety and those with lower math anxiety in study strategies are compensatory in nature. Such that, even though individuals with high math anxiety are engaging more in traditionally "less effective" study strategies that the use of these strategies has helped these math anxious individuals (especially since they are high achieving) succeed in their past. Future studies need to specifically assess the utility of these strategies for individuals with high math anxiety.

Much more work is needed in the future to elucidate the relationships between study strategies and learning outcomes in mathematics. The current study was intended to be an initial foray into the study habits of individuals with varied level of math anxiety, and therefore was more retrospective than prospective in nature. In future studies, I would like to assess learning strategies throughout the term during which students are taking their quantitative courses to get an accurate representation of the study strategies they used on a weekly or monthly basis and how these may relate to their learning outcomes. It will also be important to have a sample that is more variable in their mathematics achievement to really understand what study strategies make a difference for math learning, considering that the current sample may be inherently different since they are already high achieving in math.

Conclusion

In summary, I found that individuals with high math anxiety tend to use different learning strategies than their less anxious counterparts. It could be that individuals with high math anxiety are using their study time less efficiently, spending more time with less effective study habits such as reading notes and rehearsal and less time on more valuable strategies such as elaborating on new knowledge. However, with the current data we are unable to determine whether these differences in study strategies translate to classroom learning outcomes. Future studies need to focus on elucidating the relationship between specific study strategies and math learning specifically, and only then will we be able to have a clear idea on whether the underachievement of students with math anxiety in math courses could be partially be accounted for by inefficient learning strategies.

CHAPTER V

Discussion

The current dissertation aimed to address the lack of research available on the relationship between math anxiety, study strategies, and learning of new math material. Through four studies, I found the following:

1. Math anxiety is associated with lower learning outcomes above and beyond individual math skill. Even individuals with high math skill and course completion are negatively impacted my math anxiety.
2. It is inconclusive whether worked examples, active problem-solving, or faded examples lead to learning advantages or disadvantages for individuals with high math anxiety or low math skill. However, we did find that studying only examples was not a favorable study strategy for individuals with high math anxiety or low math skill. Suggesting that the opportunity to practice newly acquired math information is important for acquisition of procedural math information for individuals with high math anxiety or low math skill.
3. Individuals with math anxiety tend to have increased use of study strategies previously found to be less effective for learning, such as massing and rehearsal/reading, and decreased use of strategies thought to be effective, such as elaboration and help seeking, compared to their less anxious peers. In addition, individuals with high math anxiety reported greater use of spacing and organization than their less anxious peers. Together these findings suggest that individuals with

math anxiety might be using their study time less efficiently than their less anxious peers.

My findings expand our current understanding of the correlates of math anxiety by providing evidence as to its relationship with math learning and use of study strategies. However, many more questions are yet to be answered. Why do individuals with math anxiety have more difficulty acquiring new procedural math knowledge? Is it simply due to the manner in which math anxiety interferes with basic cognitive functioning, such as working memory or attentional control? Or are other processes in play, for example self-efficacy? Does it merely take math anxious individuals a longer amount of time to master new procedural math information? What about conceptual math knowledge, is it affected in the same manner? These are all questions future research should address.

Strengths, Limitations and Future Directions

There are several strengths of the current studies. First, they addressed a significant hole in our current understanding of math anxiety and its broader effects on learning. Up until recently, our knowledge of math anxiety was limited to the effects of math anxiety on existing knowledge. However, previous findings show that math anxiety is associated with greater avoidance of math related fields of study (Hembree, 1990), but the existing data does not really tell us much about the contributing factors that lead to this outcome. Our data suggest that learning new math information might be more difficult for individuals with high math anxiety, even if they have high math skill and completed advanced math coursework. If individuals are not mastering certain concepts along with their peers, this could set them up for future difficulties in more advanced courses. Such an expanding gap between individuals with high and low math anxiety over the years could have a dramatic effect on students' mastery of math by the time they are graduating high school. My findings suggest that it is not enough that we find strategies that alleviate the negative effects of math anxiety (such as those presented in Chang & Beilock, 2016), but we also need to focus on getting math anxious individuals' knowledge caught up if we are to change their prospects in pursuing math intensive fields of study. This will be especially important for women, since they tend to struggle more with math anxiety and are vastly underrepresented in STEM fields (according to the National Center for Education Statistics). Given the current importance of science, technology, engineering and mathematics for our current society, we need to foster these skills in as many students as possible for the sake of our future scientific progress and to increase in diversity and equity in STEM.

Second, the first set of studies used well powered, randomized control experiments to take a close look at the influence of specific study strategies on learning outcomes on procedural math learning with regards to individual differences in math anxiety and math skill. Although a priori power analyses were not conducted, post-hoc power analysis indicate that we had sufficient sample sizes to detect a small effect (Cohen's f = 0.1) with 95% power in the linear regressions. The specific nature of the study really allowed us to investigate the micro level influence of math anxiety on learning of a discrete mathematics topic, on which no previously published data exists. However, there are several limitations to our approach, specifically in the materials and the sample we tested. With regards to the material, we only assessed procedural knowledge and our current findings cannot speak to the effects of math anxiety on conceptual knowledge. In addition, the task was far too easy; this could be a product of the fact that we only focused on one specific topic or that the participants were overall a high achieving group. It is also possible that difference in reporting math anxiety between men and women could have impacted our results, future studies should assess men and women separately. We are also limited in the fact that several procedural changes were implemented between and within the first three studies. Future studies will need to focus on refining the materials, using a more diverse sample with regards to math skill, and assessing the influence of specific dosage of different study strategies and their influence on learning outcomes. These studies were a first foray into these questions so some limitations in methodology are to be expected, which I hope to address in my future research.

The third strength of the current dissertation is the exploration of students' actual math study habits and how these relate to individual math anxiety. Previous research is lacking as far as the specific exploration of students' reported study habits in math with relation to individual differences in math anxiety. One possible reason students with math anxiety might have lower achievement in math courses is the use of ineffective study strategies. Our findings really provide the first comprehensive evidence towards confirming this speculation. Previous studies only looked at a limited set of study strategies or specifically focused on assessing the effects of specific strategies for learning outcomes. However, the data on how effective specific strategies are for math learning specifically is far more limited than the evidence available for text learning. More work is needed to really assess if differences in study strategy use between individuals with high math anxiety and their low anxiety counterparts lead to substantial differences in learning outcomes. Also, future work should address some of the limitations in the current study mainly the need for reliable and valid scales assessing specific cognitive study strategies, such as spacing, interleaving, and testing, as well those assessing use of strategies specific to math and more technical courses, such as problem solving.

In conclusion, the current study has opened a whole new area for inquiry. It is my hope that in the future, I will use this line of work to develop evidence-based interventions to help mitigate student drop out from math intensive fields due to math anxiety, specifically focusing on mastery of math content and use of effective study strategies. Although, we know a fair amount about math anxiety this far, we still need much more work assessing its specific effects on student learning.

APPENDICES

Appendix 1 Studies 1, 2 & 3 Problem Sets

Practice Problems Order A	Practice Problems Order B	Test A	Test B
7_{10} → base 4	10_{10} → base 4	39_{10} → base 8	25_{10} → base 8
10_{10} → base 4	7_{10} → base 4	43_{10} → base 8	16_{10} → base 8
8_{10} → base 3	9_{10} → base 3	14_{10} → base 7	44_{10} → base 7
9_{10} → base 3	8_{10} → base 3	31_{10} → base 7	27_{10} → base 7
5_{10} → base 2	6_{10} → base 2	33_{10} → base 6	23_{10} → base 6
6_{10} → base 2	5_{10} → base 2	16_{10} → base 6	32_{10} → base 6
		47_{10} → base 5	28_{10} → base 5
		35_{10} → base 5	38_{10} → base 5

Appendix 2 Faded Example Condition Stimuli

Convert 5_{10} into base 2

2^2	2^1	2^0
4	2	1

— — —

5÷4= 1 R1

1 0 _

1÷1 = 1

1 0 1

Convert 8_{10} into base 3

3^1	3^0
3	1

How many places will be in the final answer?

Convert 8_{10} into base 3

3^1	3^0
3	1

— —

8÷3= 2 R2

2 2

Convert 10_{10} into base 4

4^1	4^0
4	1

How many places will be in the final answer?

Convert 10_{10} into base 4

4^1	4^0
4	1

— —

10÷4= ?

_ _
⇧
What number will go above the arrow?

Convert 10_{10} into base 4

4^1	4^0
4	1

— —

10÷4= 2 R2

2 2

Convert 655_{10} into base 20

20^2	20^1	20^0
400	20	1

How many places will be in the final answer?

Convert 655_{10} into base 20

20^2	20^1	20^0
400	20	1

— — —

655÷400= ?

_ _ _
⇧
What number will go above the arrow?

Convert 655_{10} into base 20

20^2	20^1	20^0
400	20	1

10	A
11	B
12	C
13	D
14	E
15	F
16	G

_ _ _

655÷400= 1 R255

1 _ _

255÷20 = 12 R15

1 C F

Convert 6_{10} into base 2

2^2	2^1	2^0
4	2	1

How many places will be in the final answer?

Convert 6_{10} into base 2

2^2	2^1	2^0
4	2	1

_ _ _

6÷4= ?

_ _ _

⇧

What number will go above the arrow?

Convert 6_{10} into base 2

2^2	2^1	2^0
4	2	1

_ _ _

6÷4= 1 R2

1 _ _

2÷2 = ?

1 _ _

Fill in the rest of the answer

Convert 9_{10} into base 3

Solve

?

?

Convert 7_{10} into base 4

Solve

?

?

Convert 29_{10} into base 16

Solve

?

?

10	A
11	B
12	C
13	D
14	E
15	F
16	G

Appendix 3 Math MSLQ Learning Strategies Scale

Cognitive strategies

Rehearsal

- When I study math, I memorize what I need to learn by repeating it over and over to myself.
- I study math by going over the formulas or definitions in order to memorize them.
- I study math by doing the practice problems over and over again to memorize them.
- When I study math, I write down the formulas and definitions many times in order to memorize them.

Organization

- When I study math, I make outlines to organize what I have to learn.
- I study math by highlighting or underlining to organize what I need to know.
- I study math by making charts, diagrams, or tables to organize what I need to learn.
- When I study math, I make a list of the formulas or definitions to organize what I need to know.

Elaboration

- I connect what I learn in math to what I am learning in some other classes.
- When studying math, I try to connect new material to what I already know.
- When I study math, I translate the formulas or definitions in the textbook into my own words.
- I make connections between how I solve one math problem with the way I could solve others.

Metacognitive Strategies

Planning

- I plan how I am going to study new math topics before I begin.
- Before I begin studying math I think about what and how I am going to learn.
- Before I study math, I plan how much time I will need to learn a topic.
- When I learn new topics in math, I first figure out the best way to study.
- Before I study math, I set goals for myself to help me learn.

Monitoring

- When I study math, I ask myself questions to make sure I know what I have been learning.
- When studying math I try to determine how well I have learned what I need to know.
- When I'm studying math I test myself to see whether I know the material.
- I check whether I have learned what I am studying in math.

Regulation

- If I get confused with something I'm studying in math, I go back and try to figure it out.
- If the math I am studying is difficult to learn, I slow down and take my time.
- If I'm having trouble solving math problems I try other ways to solve them.
- If I think I don't know my math well enough, I make sure I learn it before going to the next topic.

Resource Management Strategies

Help seeking

- If I don't understand something in math I ask my teacher
- for help.
- If I don't understand something in math I ask other students for help.

- If I don’t understand something in math I ask for help to better understand general ideas or principles.
- If I don’t understand something in math I ask others for the answers I need to complete my work.

Time and study environment management

- I study math in a place where I can concentrate.
- I use a study schedule when preparing for math exams.
- I study math at a time when I can concentrate.
- I make sure I have as few distractions as possible when I study math

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