Math Anxiety and Predictors that Influence Arithmetic Fact Storage

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Abstract

Previous work proposed negative consequences of math anxiety on mathematical development by creating performance-related worries and intrusive thoughts that deplete the working memory resources for the math task at hand. However, those works focused in-depth on one psychological aspect (e.g., cognitive); thus, the current study aimed to fill this gap with the consideration of multiple perspectives (developmental, cognitive, anxiety-related) and explored predictors that influence people's arithmetic fact storage in long-term memory. Participants (N = 202) performed two memory interference tasks (multiplication, picture-word agreement; each contains three types of problems, including true, related, and unrelated), a working memory capacity task (backward digit-span), and a questionnaire task that measured negative emotionality (including anxiety and closely-related constructs), math anxiety, insecure and secure attachment. As a result, we found that working memory capacity and math anxiety predicted math performance but not picture word performance. There was some evidence that working memory differences mediated the relationship between math anxiety and math performance. In addition, participants showed considerable memory interference effects in multiplication and picture-word tasks in terms of response time and accuracy, and this effect was found to be larger for the problems involved in math than picture-word. In contrast to absolute math performance, the multiplication interference effect did not vary with working memory or math anxiety measures, but attachment anxiety was positively related weakly to both multiplication and picture-word task interference. Taken collectively, the results imply some degree of independence between predictors of absolute math (i.e., multiplication) and associative interference effects in multiplication retrieval.

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Table of Contents

List of Tables

List of Figures

Introduction and Literature Review

As technology is progressively making astounding advances, mathematical skills are essential for individuals and society. However, not everyone enjoys doing math. Some individuals despise it and feel incapable of doing arithmetic because of fear and anxiety. These individuals have what is typically referred to as math anxiety, which is "feelings of apprehension and tension concerning manipulation of numbers and completion of mathematical problems in various contexts" (Richardson & Suinn, 1972, p. 551). The incidence and prevalence of math anxiety are mixed due to samples taken from various regions for testing. One of the most extensive data is the Programme for International Student Assessment (PISA). Their 2012 assessment was tested across 34 Organization for Economic Co-operation and Development (OECD) countries. Within such a large sample, 59% of students aged between 15 to 16 found themselves very worried and anxious about the difficulty of math class. Furthermore, 33% suggested their tense feeling, especially when the math homework must be done; another 31% reported nervousness when doing math problems. These data sufficiently represented that math anxiety is a worldwide and widespread issue in our society, and it is worth researching it in more depth.

Research about math anxiety has been approximately 65 years of history since the first empirical research by Dreger and Aiken (1957), who used the term "number anxiety" as a label for emotional reactions to numbers and math. In their research, 704 undergraduate students from Florida State University were recruited. During that time, no scale was designed specifically for math anxiety. Therefore, researchers used three math-focused questions to measure math anxiety and used the 47-item Taylor Manifest Anxiety Scale (TMAS; originally 50 items, three low validity items were dropped) to measure broader forms of non-math anxiety. Based on scores from both TMAS and three math questions, four groups of participants were formed, including people with both high non-math anxiety and number anxiety, those high in one and low on the other and vice versa, and those low in both. Ten participants were randomly selected from these four groups to be a subsample that performed the arithmetic test. After clusters of analyses, three conclusions were made. First, number anxiety appeared to be a separate construct from other broader forms of anxiety. Second, number anxiety does not relate to general intelligence. Third, high number-anxious individuals tended to have lower math grades.

Dreger and Aiken's work raised people's attention to math anxiety. Moreover, it led to a new trend of investigation during the 1990s, the interest in separating math anxiety from other forms of anxiety and the investigation of personality factors associated with it (e.g., self-confidence, enjoyment, self-efficacy; McLeod, 1989). Meanwhile, another stream of researchers endeavoured to develop scales and measurements specific to math anxiety (e.g., Richardson & Suinn, 1972; Alexander & Martray, 1989) and was eager to explore possible cognitive underlying models for math anxiety (e.g., Ashcraft & Faust, 1994).

Early exploration of math anxiety made great success on the personality, emotional, and cognitive features of math anxiety, but they typically get in-depth with investigating one single aspect of math anxiety rather than combing other factors. The current research aimed to fill this gap by considering multiple psychological perspectives and exploring math anxiety and its underlying mechanisms as a whole. The following section of the current thesis will give a detailed introduction to the origins of math anxiety, the possible reasons why high math-anxious people did poorly in mathematics, and the underlying cognitive mechanisms that lead to such poor performance.

1.1. The Origin of Math Anxiety: Insecure Attachment

"Feelings of apprehension and tension…" (Richardson & Suinn, 1972, p. 551); this part of the math anxiety definition indicated the possibility of the shared emotional feelings between math anxious individuals and those with other broader forms of anxiety problems. Only a few studies investigated the origins of math anxiety, and they found the development of math anxiety in primary school students and the relationship between math anxiety and poor math performance (e.g., Young et al., 2012). In contrast, research about the origins of broader anxiety-related problems has been well established, of which the main focus was attachment styles.

Children's attachment is typically defined as an emotional bond that is long-lasting and is built towards attachment figures such as parents and caregivers (Ainsworth, 1989). During forming the bond, there is an intrinsically interwoven relationship between attachment and anxiety systems (Bowlby, 1969). Reasons contributing to anxiety-related problems can be varied, but data has convincingly shown that the maladaptive coping strategies developed during insecure attachment relationships were the main contributors (Brumariu and Kerns, 2010). As human beings, we encounter threats from the environments we live in. From an evolutionary perspective, those threats activate children's attachment system and further facilitate motivation or focus to seek support and proximity (Cassidy & Shaver, 2016). Depending on the responsiveness of caregivers, children will develop secure or insecure attachment styles. Securely attached children love their caregivers and regard them as safety grounds for spending plenty of time and patience to fulfill needs. Secure feelings can further foster children's ability to deal with troubles and help them better cope with anxiousness. Children become insecurely attached if there is a lack of responsiveness and care. They can be more anxiously attached, especially when trying to get their needs but fear that no one will help them. As a result, they become hypervigilant and cannot adaptively deal with distress. Insecure children may be more avoidantly attached or distance themselves from their caregivers. In this case, these children no longer seek support by suppressing all emotions and avoiding the sources of distress (Brumariu & Kerns, 2010).

As mentioned above, insecure attachment (attachment anxiety, attachment avoidance) was identified as the origin of broader anxiety-related problems. Considering the overlapped emotional responses between math anxiety and other anxiety problems, researchers made a parallel link to the emergence of math anxiety. Bosmans and De Smedt (2015) were the pioneering research that indicated math anxiety as a maladaptive affect regulation mechanism involving the characteristics of insecure attachment. Eighty-seven primary school children (M_{age} = 10.34 years) were recruited and first fill out an insecure attachment questionnaire (the Experiences in Close Relationships Scale-Revised, adapted version for children as the ECR-RC by Brenning et al., 2011) and a math anxiety questionnaire (The Mathematics Anxiety Rating

Scale for Adolescents; MARS-A; Suinn and Edwards, 1982). Then, they completed a timed and untimed standardized test of math achievement. The timed test involved five columns of 40 single-digit basic arithmetic, including additions, subtractions, multiplications, divisions, and mixed problems. Children were asked to solve each column as fast and accurately as possible within 1 min. The untimed test was curriculum-based, which contained 60 items that covered a variety of mathematical skills such as number knowledge, calculation, word problem solving, measurement, and geometry. The results showed that children with insecure attachment styles have significantly higher levels of math anxiety regardless of age, sex, and IQ. Also, math anxiety was negatively associated with timed and untimed measures of math performance. Bosmans and De Smedt's work focused on the developmental perspectives of math anxiety but did not explains the way math anxiety contributes to poor math performance. Instead, research from cognitive perspectives gave more hints about the reasons.

1.2. Anxiety-induced Working Memory Depletion

Math-anxious individuals worry too much about math situations, this is one prominent feature of math anxiety, and worries may aggravate the strain of mental effort and further influence the performance of later math tasks. From a cognitive perspective, the processing efficiency theory mentions the negative consequences of worrying (Eysenck & Calvo, 1992). Worries occupy people's consciousness and consume the resources of the limited working memory system. In other words, the theory predicted quite specifically that an anxious individual should show disruption on a cognitive task to the extent that the task relies on working memory resources. Even though this idea was aimed at explaining anxiety-related disorders, it implied that the feelings of worry might play an essential role in math anxiety research. Interestingly, before the processing efficiency theory, Ashcraft and Faust brought up a similar idea concerning the cognitive consequences of being worried and utilized it in math anxiety research in their 1988 conference report. When the study was subsequently published (Ashcraft & Faust, 1994), it appeared to be the first to propose whether math anxiety influenced the mental processing involved in arithmetic. In their exploratory study, college students were categorized into four math anxiety groups (from low to high) after the assessment using the Mathematics Anxiety Rating Scale (MARS; Richardson & Suinn, 1972). Participants were then asked to perform simple addition and multiplication problems (e.g., 4 + 3 = 7, 8 × 4 = 32), two-digit addition problems with or without a carry (e.g., 24 + 11 = 35, 24 + 19 = 43), and complex problems containing all four arithmetic operations. (e.g., 18 + 16= 34, 47 – 18 = 29. 12 × 14 = 168, 156 ÷ 12 = 13). As a result, significant processing differences in simple addition and multiplication were found when participants were divided by quartiles into anxiety groups. Much larger differences in processing speed and accuracy were found with complex addition problems and a set of difficult problems that tested all four arithmetic operations. Overall, the low, anxious group was consistently the most rapid and accurate, the medium-high was the slowest, and the high anxiety group was the most prone to errors.

After the initial study, one of the authors, Faust (1996), changed the old paradigm and found several additional effects of math anxiety on cognitive performance. In simple addition problems, Faust expanded the range of value (or in other words, "split") for the incorrect answer; here, incorrect answers could be wrong by 1, 5, 9, or 23 compared to the correct one (e.g., 5 + 7 = 35). Unlike the typical result showing improved performance as the split grows later, Faust found that higher math-anxious groups made more errors and had more extreme scores when the split increased. This result reflected an issue of deficiency in the number sense, which is the expectation for people to immediately reject those unreasonable answers (e.g., 35 for 5 + 7) based on a plausibility judgment. Moreover, these people also had slower response speed with lower accuracy when the two-digit addition problems involved carry operation. To rule out a simple math competence as a confound in explanations of the effects of math anxiety, Faust tested all experimental stimuli in an untimed, paper-and-pencil format in a separate study. No relationship was found between performance and measured level of math anxiety, either in correlations or in the analysis of variance with all four math anxiety level groups; thus, the time pressure factor was removed. Taken together, results from the initial and Faust's replication studies were impressive because they raised people's reflection on the processing efficiency theory and inspired later research on testing the relationship between math anxiety and working memory.

One influential research was done by Ashcraft and Kirk (2001); they further extended the processing efficiency theory to the realm of math anxiety and conducted a direct test of the hypothesis that math anxiety disrupts working memory processing while doing math, visibly only when the math task relies on the resources of working memory. Ashcraft and Kirk used a typical way of testing, the dual-task setting, in which participants performed in three conditions: arithmetic-only, letter-only, and dual-task conditions. In the arithmetic-only condition, participants performed addition problems of increasing difficulty. The problems include basic facts (single-digit operands), medium-size problems (two-digit plus one-digit operand), large problems (two two-digit operands), and half of the problems require a carry operation. In the letter-only condition, two or six random letters were shown prior to the addition problem, and participants recalled them after the addition problem was removed from the computer screen. Participants did not need math processing because the addition problems with answers were shown to be read aloud. In the dual-task condition, the letters had to be held in working memory while solving the addition problems, and participants recalled the letters from memory after answering addition problems. If the processing efficiency theory (Eysenck & Calvo, 1992) is accurate, the dual-task interference effect should be especially pronounced for the high math-anxious group because those people performed in a triple-task situation. This means that the difficult arithmetic problems were solved under a heavy working memory load while anxiety-induced worries were draining their working memory. As expected, higher working memory loads in the dual-task condition led to high math-anxious individuals being vulnerable to errors, especially when arithmetic problems involved carry operation. In the letter-only condition, the letter recall was nearly perfect. In the arithmetic-only condition, the high math-anxious group scored almost 40% errors on the working memory task when the working memory load was high and the problem involved a carry, compared to 18% for the low math-anxious group. These two groups had identical error rates in the six-letter load condition when the problem did not involve carrying. Therefore, the critical role of working memory in the procedure of carrying was confirmed, and the crippling of working memory on the part of highly math-anxious participants was also demonstrated. In brief, Ashcraft and Kirk's work revealed that those worries, intrusive, or rumination thoughts about mathematic negatively influenced high math-anxious individuals by overloading their working memory resources. Nevertheless, other factors may also contribute to people's poor math performance.

1.3. Proactive and Retrieval Memory Interference

Arithmetic facts may contain certain features contributing to people's vulnerability to poor math performance. Arithmetic fact storage is sequential learning of number associations with very similar elements (the ten digits from 0 to 9). When children learn arithmetic facts by rote, they have to learn distinct associations with many features in common. For example, single-digit multiplication facts involve three main elements, including the two operands and the product. Children learn $6 \times 7 = 42$, but also $6 \times 8 = 48$. These two multiplication equations have a common component (the number 6) and the decade of the answer. The similarity of arithmetic facts has been described in Campbell (1995). According to his connectionist model, simple arithmetic problems are made of nodes, and these nodes receive similar-based excitatory input during retrieval and will complete until one of the nodes reaches a critical threshold. While Campbell's work is mostly concerned with the interference of arithmetic facts during the retrieval stage, he also suggested that arithmetic fact learning may suffer from proactive interference (Campbell & Graham, 1985), meaning that, at the working memory level, previously encoded information about numbers makes it challenging to store new coming related associations. The more common features items have, the less likely they will be held in memory due to interference, and the amount of features overlapped determines the degree of proactive overwriting or the encoding strength (Farrel & Lewandowsky, 2002). Hence, when a considerable level of overlap shows up, children are confronted with proactive interference from previously learned arithmetic facts and interference from all numbers in their working memory.

Building upon the idea of proactive working memory interference, De Visscher & Noël (2013; 2014) made a parallel line of thinking to the arithmetic fact storage in long-term memory. Their research used “hypersensitivity-to-interference” to describe the memory confusion due to the overlapping features of arithmetic fact storage. They suggested that if the encoded information is already contaminated by proactive interference at the working memory level, then such a poor quality of information may further interfere with the long-term memory and arithmetic fact storage. In 2013, De Visscher and Noël tested one patient with a high level of cognitive functioning but a specific impairment of arithmetic facts encoding. After a recent-probes task and associative memory tasks with a controlled level of interference, the patient had hypersensitivity-to-interference in memory. De Visscher and Noël argued that this could explain the patient’s difficulties building an arithmetic facts network in long-term memory. However, this study was only based on a single case. Later on, the same group of researchers conducted another experiment.

In 2014, to evaluate the impact of sensitivity to interference on arithmetic fact acquisition, De Visscher and Noël tested 101 fourth-grade children who were at the end of the year and learned all multiplication tables. After a series of arithmetic facts fluency tests (36 single-digit multiplications, 40 single-digit additions, and 32 complex two-digit additions; excluding 0 and 1 as operands), De Visscher and Noël selected 23 children who presented low arithmetical fluency and control children from the same classroom (all matched for age and gender). The two groups were then submitted to a new associative memory paradigm, including low versus high interfering associations. This new task allowed them to test whether children with low arithmetical fluency presented impaired associative memory or hypersensitivity-to-interference in the context of associative memory. The new paradigm involves two aspects; the associative memory aspect is referred to by the idea of paired-associate learning, which involves an encoding phase and a retrieval verification phase; the proactive interference aspect contains a recent-probes task. According to these two aspects, De Visscher and Noël used pictures of 35 famous cartoon characters (e.g., Sponge Bob) and 35 locations (e.g., Paris) as stimuli. Children were asked to memorize where the cartoon character was during the learning phase, and then they were successively presented with three different associations of characters and locations. Directly after these three presentations, a purple screen with the word "verification" appeared in the center of the computer screen, and children verified whether the associated display was true or false by pressing "S" (true) or "L" (false) on the keyboard. Twenty blocks consisting of three associations followed by three verifications were displayed, and the task took approximately 15 minutes to complete. The 60 verification trials were built based on the type of answer (true/false) and the level of interference (low/high). Within the 30 true verifications, 15 were low-interference because they were new items children had never seen before the learning phase. The other 15 were high-interference because the same pictures had been associated differently in the previous block (e.g., in the first block, Asterix was in the mountains and Marsupilami was in the shop, and in the second block, Asterix was in the shop in both the learning and verification phase). The 30 false verifications involved 10 low-interference, 10 high close-interference, and 10 high remote-interference trials. The low-interference consisted of one picture from the learning phase and one new picture (locations or characters). The high close-interference incorrectly paired one character and one location encountered during the current block. The high remote-interference contained associations that were incorrect in the current block, but that corresponded to associations that had been learned in the previous block (e.g., Sponge Bob was in the garage in the first block, then in the mountains in the learning phase of the second block; in the verification phase of the second block the participant had to reject the association Sponge Bob – garage).

After testing, the results revealed that children with low arithmetical fluency were subject to a higher sensitivity-to-interference in associative memory than typical arithmetical fluency children. These children performed very similarly to the controls when they encountered low-interference associations, but their performance in high-interference questions was significantly lower than that of the controls. Their impairment in the high-interference condition clearly indicated the sign of an abnormal proactive interference, and their normal performance in the low-interference condition suggested their typical associative memory in general. Low arithmetical fluency children experienced hypersensitivity-to-interference in the working memory level, and this proactive interference could further lead the retrieval interference and prevent the storage of the arithmetic facts in the long-term memory. Therefore, the results support the hypothesis that hypersensitivity-to-interference in memory is related to weak arithmetic facts storage in long-term memory. Overall, De Visscher and colleagues' work looked at another way how memory interference influences people's math performance. To some extent, it provided new thinking about viewing math anxiety, which inspired an idea about exploring the susceptibility-to-memory-interference of those high math-anxious individuals.

1.4. The Current Study

The above section has introduced the issue of math anxiety and its influences on math performance from either developmental or cognitive perspectives. With the consideration of multiple perspectives, participants in the current study performed four tasks, including two memory interference tasks (multiplication, picture-word), a working memory capacity task (digit-span backward recall), and a questionnaire task that contained measures of anxiety (negative emotionality scale, math anxiety scale) and attachment (insecure attachment, secure attachment). The two memory interference tasks involved the same paradigm of problem type, including true, related and unrelated problems (the performance difference between related and unrelated problems suggested the memory interference effect). All tasks were computerized, and participants took up to one hour to complete.

1.4.1. Hypotheses

The two main tasks in the current study are the multiplication and picture-word tasks. The performance of these two tasks regarding response time (RT) and accuracy (ACC) is our dependent measure. Comparing the performance of the two tasks, we expected participants to spend more RT with lower ACC on multiplication than on the picture-word task. The main reason for this assumption is that the difficulty level in the multiplication task was relatively higher than in the picture-word task. Furthermore, because both tasks involved the same paradigm of true, related, and unrelated problem types, we expected to see the difference between these three problem types for both tasks, of which participants would spend more RT time with low ACC in the related compared to unrelated problems. We did not expect differences in the size of interference effects between the two tasks, according to Heidekum et al. (2019).

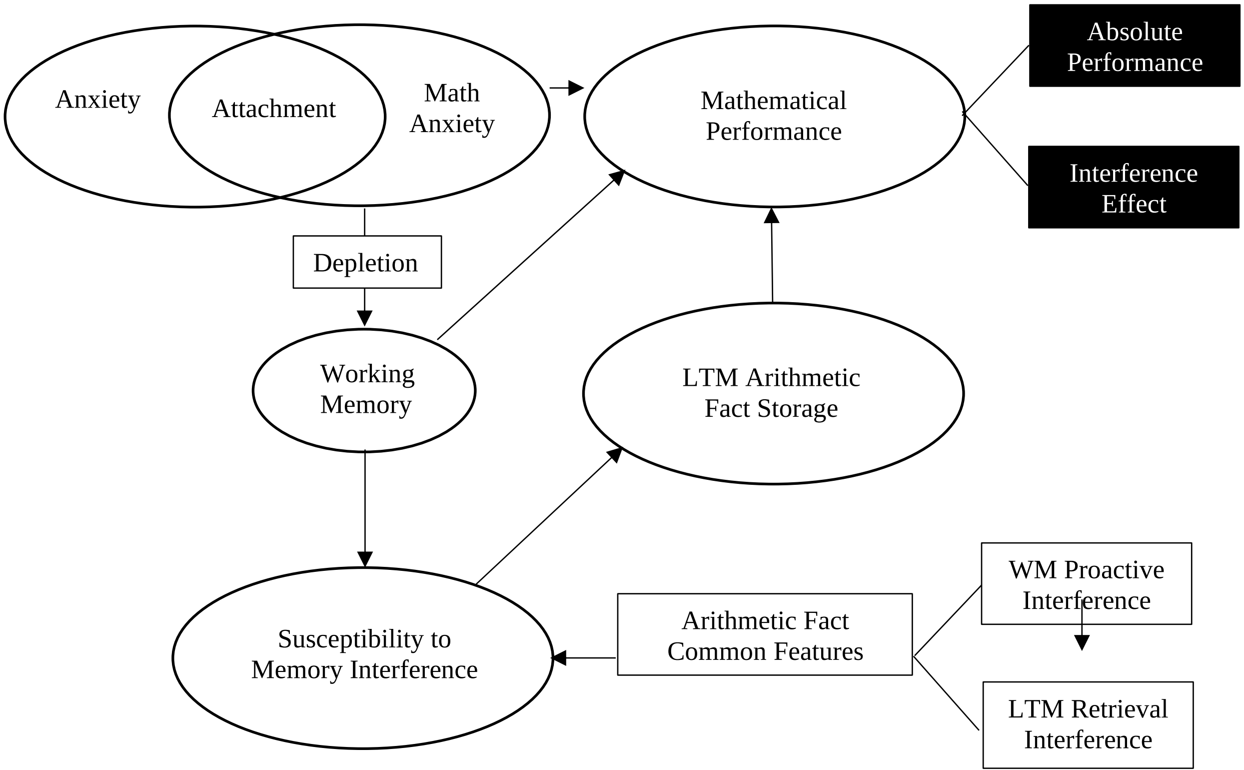

Figure 1. Illustration of Rationale and Hypothetical Structure

Figure 1 shows the hypothetical structure of the current study using the multiplication task as an example. We created this graphical illustration for the multiplication task only because the picture-word task served as a non-mathematical interference control condition. As abovementioned, we focused on dependent measures of performance, e.g., we measured absolute performance and interference effect for multiplication task (the black boxes shown in Figure 1).

The absolute performance measured the RT and ACC performance of the true problem type (e.g., 2 × 5 = 10). For this dependent measure of performance, we aimed to replicate previous research on identifying how working memory capacity influenced math performance, of which we expected that participants with high working memory capacity tend to spend less RT time with high ACC on the multiplication task (Ashcraft & Kirk, 2001; Heidekum et al., 2019). We also aimed to find the negative correlation between working memory capacity and math anxiety as a support for the "worry account," in which high math-anxious individuals tend to show low ability to perform working memory tasks (e.g., Ashcraft & Kirk, 2001). Moreover, we sought to identify math anxiety as a predictor of math performance, which high math-anxious individuals are expected to associate high RT and low ACC on the multiplication task. All these associations are hypothesized to be math-specific, so we will not observe parallel correlations between absolute performance of the picture-word task and math anxiety or working memory capacity scores. We also sought to identify insecure attachment as an origin of math anxiety; specifically, based on scores from attachment anxiety and avoidance scales, high math-anxious individuals were more insecurely attached relative to low math-anxious individuals (Bosmans & De Smedt, 2015). Moreover, we did not expect the relationship between scores from negative emotionality (which includes a non-math-specific anxiety subscale) and math anxiety because math anxiety may be distinct from other forms of negative emotionality (e.g., anxiety not related to math; Dreger & Aiken, 1957).

Another dependent measure of performance in the current study is the interference effect. This is measured as the percentage costs in RT and ACC for related problems relative to unrelated problems. Building upon hypotheses of absolute performance, if math-anxious individuals were insecurely attached and this limited their working memory capacity, it was reasonable to expect these people to show higher susceptibility to memory interference. In other words, they should show a high math interference effect on math performance because these interferences were raised by the common features of arithmetic facts and the presumed link between proactive interference and attachment. If interference is indirectly influenced by attachment components (e.g., attachment security) that is general than math-specific, then this relation will emerge for both interference tasks.

In summary, the current study aimed to replicate previous research findings on how working memory and math anxiety influenced math performance. On top of these, we also aim to explore other predictors (e.g., negative emotionality, attachment anxiety, attachment avoidance, and attachment security) that could contribute to people's poor performance in mathematics.

2. Methods

2.1. Participants

Two hundred and two participants (97 females) participated in the current study. Participants age ranged from 18 to 35 (M_{age} = 22.310, SD = 2.389), with 180 right-handedness, 18 left-handedness and 4 both-handedness. The participants' first language for arithmetic varied, of which 63.4% speak English, 16.4% Spanish, 8.9% Portuguese, 3.5% Italian, 3% Polish, 2.5% Greek, and 5.3% for others, including Hebrew, Hungarian, Indonesia, Portugal, and Slovenian. Participants were recruited remotely either via the Department of Psychology and Health Studies Participant Pool using SONA or Prolific. As compensation, SONA participants received two bonus credits per hour of participation for a psychology course at the University of Saskatchewan, and Prolific participants received £7.50 per hour. All experimental procedure has received approval from the Research Ethics Board at the University of Saskatchewan.

2.2. Apparatus

The current study was conducted entirely online, and a Microsoft Windows computer was necessary for participants to perform tasks in their location. The experiment was controlled by E-Prime 3 software (Psychology Software Tools, Inc., http://www.pstnet.com). The software feature E-Prime Go allowed participants to download task links, with the data written to the researcher's E-Prime Go account for further analyses.

2.3. Stimuli and Design

2.3.1. Questionnaires

There were four questionnaires, which resulted in 158 items in total. Each item was displayed on the center of the computer screen, with Likert scale options and a Next button directly below it. All items were in black Consolas font, size 18, against a white background. There was no right or wrong answer, and the order of the four questionnaires was fixed with presenting negative emotionality measures first, followed by insecure attachment, math anxiety, and secure attachment measures.

Negative Emotionality. The current study utilized the Big Five Inventory-II (BFI-II; Soto & John, 2017) to measure personality traits. BFI-II scale involved 60 items, with five subscales including extraversion, agreeableness, conscientiousness, negative emotionality, and open-mindedness. The 12-item negative emotionality scale entailed a subscale for anxiety (4-item) and closely related constructs, as such negative emotionality served as a more generalized proxy for non-math-related negative emotionality including anxiety. All 60 items were rated on a 5-point Likert scale ranging from Disagree strongly (= 1) to Agree strongly (=5).

Insecure Attachment. The 36-item Experiences in Close Relationships Scale-Revised (ECR-R; Fraley et al., 2000) measured two dimensions of adult insecure attachment (attachment anxiety and avoidance). Attachment anxiety was measured with 18 items that assess feelings of abandonment and desires for interpersonal merger towards partners (e.g., “I am afraid that I will love my partner’s love”). Attachment avoidance was assessed with another 18 items that tap into discomfort about closeness, dependence, or intimate self-disclosure towards partners (e.g., “I prefer not to show a partner how I feel deep down”). All items were rated on a 7-point Likert scale ranging from Strongly disagree (= 1) to Strongly agree (= 7).

Math Anxiety. Math anxiety was measured by using the Short Math Anxiety Rating Scale **(**SMARS; Alexander & Martray, 1989), which contained 25 items assessing how participants would feel during various situations that involve math (e.g., “Studying for a math test”). Items were rated on a 5-point Likert scale ranging from Not at all (= 0) to Very much (= 4).

Secure Attachment. Secure attachment was measured by the Secure Attachment Scale (McWilliams & Coveney, 2020), which involved 37 items that assess the single dimension of attachment security (e.g., “How happy are you with your close relationships?”). The Secure Attachment Scale involved three response options (very, moderately, and mildly) in the negative and the same in the positive direction. Items were rated on a 6-point Likert scale ranging from Very in the negative direction (= 1) to Very in the positive direction (= 6). Note that the Secure Attachment Scale involved five subscales, including the 14-item sense of support and respect scale, 7-item emotional awareness subscale, 7-item emotional regulation capacity subscale, and 2-item attunement to other’s emotion subscale. Because these were not our primary interests, we used the total score rather than breaking it down into subscales.

2.3.2. Working Memory Task

The current study utilized a traditional Digit-span backward task to measure working memory capacity for numbers. A series of digits were presented on the center of the screen; they were in black Consolas font, size 22, against a white background. The minimum length of digits was 2 (e.g., 68), and the maximum length was 8 (e.g., 85496371). Depending on participants’ correctness, the Digit-span backward task would adjust automated about difficulty. If two answers were correct on a block, then digit length increased. If only one was correct, the block of trials was repeated with different numbers but the same digit length. If there were no correct answers for a particular digit length, the task concluded.

2.3.3. Math Interference

The current study adapted the math interference task from Meagher and Campbell (1995). Stimuli were single-digit multiplication problems and products ranging between 2 × 2 and 9 × 9. The two digits in each problem were separated by an operation sign (×), and the problem and the product were connected by an equal sign (=). The multiplication equations were in black Courier New font, size 18 against a white background, and were presented horizontally at the center of the computer screen. All of the problems were in verification format, in which participants pressed a keyboard key to indicate a true or false equation response. Three primes were assigned to these arithmetic problems: correct, related, and unrelated (see Appendix A). The correct prime was the correct answer to the multiplication problem (e.g., 2 x 3 = 6). The related prime was the solution from another but operand-related multiplication problem (e.g., 2 x 3 = 12). Finally, the unrelated prime was a number that was not evenly divisible by either of the problem's operands but which was correct for another of the multiplication problems tested (e.g., 4 x 8 = 27, except for the unrelated equation 2 x 3 = 13). There were 108 trials; problems were distributed into three blocks with 36 problems per block. There were twelve of each answer condition (correct, related or unrelated) in each block, and across blocks, each problem was tested once in each condition. The assignment of problems to a given order of conditions across blocks was random.

2.3.4. Picture-word Interference

The current study adopted the picture and word stimuli from Heidekum et al. (2019; see Appendix B). Instead of using German word stimuli as in the original paper, the present study used the English version to test participants in Canada. Picture-word pairs were presented at the center of the computer screen, and participants judged whether the meaning of the word shown matched the concept displayed in the picture. All word stimuli were in Consolas font, size 18 and black colour. There were 32 black and white line-drawing pictures, and these pictures depicted 32 different English one-word concepts from six semantic categories: animals, insects, plants, fruits, tools, and clothing. The picture and the word were presented simultaneously with an equal sign (=; located at the center of the screen or position 50%) separating the picture (located slightly left, position 34%) and the word (located slightly right, position 66%). As in the math interference task, picture-word pairs represented three conditions: correct, related, and unrelated. The correct condition showed a picture with its correct word (e.g., the picture of “dog” = the word “dog”). The related condition paired a picture with a word from the same semantic category (e.g., the picture of “dog” = the word “cat”). The unrelated condition assigned the picture with a word from another semantic category (e.g., the picture of “dog” = the word “boot”). The picture-word task involved one block of 96 trials, and the three conditions were evenly distributed with 32 trials per condition. Moreover, trials were independently randomized for each participant.

2.4. Procedure

Because of the online operation, participants were recruited from SONA and Prolific, and the Eprime Go feature of the Eprime 3 software was the exclusive source for data collection. To exclude the confounding variable of carry-over effects between the two interference tasks, the current study created two experiment versions, and each version contained the same tasks except for interference-task order. Version 1 began with an Eprime Go link for the math interference task, followed by the picture-word interference task, working memory task, and fix-ordered questionnaires (negative emotionality, insecure attachment, math anxiety, secure attachment). Version 2 began with the link for the picture-word interference task, the math interference task and everything else. These two versions were mutually exclusive, meaning that participants were eligible to register for only one of the versions. After signing up for either version on either SONA or Prolific, when participants opened the task link, an Eprime Go website page would first pop up and ask their permission to download the task. Once the download was completed and participants opened the task file on their local computer, they would be first presented with a start instruction that included information about a consent form. If they consent to participate, the first task will start by clicking the Next button. Moreover, participants could withdraw from the study at any time, for any reason, without any explanation by pressing Alt + Shift + Enter on the keyboard. Once withdrawn, participants would be presented with a stop instruction containing a link to the debriefing form, which gives more details about the nature of the current study.

2.4.1. Demographics

Before the main tasks, each participant answered several demographic questions: SONA number for SONA participants or Prolific ID for Prolific participants, participant number (enter 1 if the birth date falls on an odd-numbered day of the month, enter 2 otherwise), session number (1 is the default), age, sex, handedness, and first language for arithmetic (for math interference task only).

2.4.2. Questionnaires

There was no fixation point or fixation cross displayed before each trial. There was also no feedback because there was no right or wrong answer. Participants clicked the mouse to select the most appropriate answer, and the questionnaire item remained on the screen until participants clicked the Next button. The time to complete all questionnaires was approximately 15 minutes.

2.4.3. Working Memory Task

Each trial started with a fixation cross that remained on the center of the computer screen for 1000 msec; this was followed by a one-digit stimulus and another fixation cross successively (each presented for 1000 msec). Then, a response instruction and an empty response box appeared, and participants were asked to type the digit sequence backward into the box using the keyboard. The box remained on the screen until participants pressed Enter to the subsequent trial. The time for completing the task depends on the participants’ correctness, and it took up to 15 minutes to complete all trials.

2.4.4. Math Interference Task

Each trial began with a fixation dot that remained on the center of the computer screen for 500 msec, followed by a central dot flashed on and off twice for 250 msec each. Two response options (0 and 1) were presented simultaneously above the fixation points, of which one option was slight to the top left side, and the other was slight to the top right side. Next, a single-digit multiplication equation appeared in the center. The arithmetic equation would stay on the screen for a maximum of 3000 msec, and participants pressed 0 or 1 on the keyboard to verify whether the displayed equation was true or false. The value assigned to the response options was counterbalanced based on whether the participant number was even or odd. Participants with odd participant numbers pressed 0 (1 if even) to indicate the equation was true and pressed 1 (0 if even) if they thought it was false. Whatever the participant numbers, 0 always appeared on the top right side of the screen, and 1 was on the top left side. Once the response was made, a feedback page with information about the response time for the given question and cumulative average percent correct appeared for 1500 msec. Feedback was displayed in Consolas font, size 18, with blue (Correct) or red (Incorrect or No response). The OR task took approximately 15 minutes to complete.

2.4.5. Picture-word Interference Task

Every trial started with a fixation cross at the center of the computer screen for 500 msec. A picture-word pair appeared in the center, with two response options (0 and 1), one located on the top left of the screen and the other on the top right. The picture-word pair remained on the screen for a maximum of 3000 msec, and participants pressed 0 and 1 on the keyboard to indicate their response. Corresponding to the math interference task, the value assigned to 0 and 1 varied on participant numbers' odd and even properties. Odd-numbered participants pressed 0 (1 if even) if they thought the picture and the word were the same and pressed 1 (0 if even) if they felt the picture and the word were different. For both types of participant numbers, 0 was always positioned on the top right side of the screen, and 1 was on the top left side. After responding, a feedback page about the response time for the given question and cumulative percent correct appeared on the screen for 1500 msec. All feedback was in Consolas font, size 18, with blue (Correct) or red (Incorrect or No response), and the PW task took approximately 15 minutes to complete.

3. Results

The dependent measures of performance of multiplication and picture-word tasks were analyzed in terms of mean response time (RT) and mean accuracy (ACC). In the following section, we first introduced results about the RT and ACC comparison between two tasks, this is achieved by performing 2 (task: Multiplication vs. Picture-word) × 3 (problem type: true vs. related vs. unrelated) Analyses of Variance (ANOVA) using GLM repeated measures procedure. We also made comparisons on the size of memory interference effects by performing t-tests. Then, we conducted correlation matrices between predictors (working memory, math anxiety, negative emotionality, attachment anxiety, attachment avoidance, and attachment security) and participants' performance on true problem type (absolute performance) and memory interference measures. Note that, for tests that violated the sphericity assumption, the degrees of freedom were adjusted using the Greenhouse-Geisser correction. Moreover, pairwise comparisons were reported using the Bonferroni correction for multiple comparisons. All data analyses were done using the SPSS v28, and all analysis outputs are available at OSF (https://osf.io/3xacz/?view_only=560b302e1a464929a38e6abdf06f1fa1).

3.1. Task Comparisons: Response Times (RTs)

The current study first conducted the RT analysis that only involved trials with correct responses, and mean RT as a function of task and problem type appears in Table 1. There was a main effect of task, $F(1, 201) = 342.635$, $p < .001$, $\eta_p^2 = .630$, indicating longer mean RTs for multiplication ($M = 1204.134$, $SE = 19.190$) than the picture-word task ($M = 868.719$, $SE = 11.593$).

Table 1. Mean response time and accuracy for picture-word and multiplication tasks

Task	True		Related		Unrelated	
	Mean RT	ACC	Mean RT	ACC	Mean RT	ACC
Picture-Word	874(167)	88(10)	895(181)	86(8)	837(163)	96(6)
Multiplication	1195(266)	78(15)	1266(299)	75(13)	1151(279)	88(11)

Note: Mean RT (in milliseconds) and ACC (in percent correct). Standard deviations are in parentheses.

An effect of problem type occurred, *F*(1.838, 369.370) = 134.817, *p* < .001, η_p^2 = .401), because averaging over the two tasks, participants were slowest to respond to related problems (*M* = 1080.745, *SE* = 14.103) followed by true (*M* = 1034.572, *SE* = 12.742) and unrelated problem types (*M* = 993.963, *SE* = 13.208) (*p* < .001 for all pairwise comparisons).

The main effects were qualified by the Task × Type interaction, *F*(2, 402) = 20.054, *p* < .001, η_p^2 = .091. To investigate the interaction, we separately analyzed the effects of problem type for the two tasks. For the picture-word task (see Table 1.), the main effect of type [*F*(2, 402) = 57.563, , *p* < .001, η_p^2 = .223] reflected that participants completed unrelated problems the fastest (*M* = 837.307, *SE* =11.496) followed by the true (*M* = 873.619, *SE* = 11.722) and related problems (*M* = 895.233, *SE* = 12.784) (*p* < .001 for all pairwise comparisons). The corresponding analysis for the multiplication task confirmed an effect of type [*F*(1.898, 381.559) = 91.220, , *p* < .001, η_p^2 = .312], of reflected the unrelated problems was still the fastest to complete (*M* = 1150.619, *SE* = 19.645 ; true: *M* = 1195.525 , *SE* = 18.732 ; related: *M* = 1266.257, *SE* = 21.035; *p* < .001 for all pairwise comparisons among problem types for the multiplication task).

In summary, both tasks presented significant RT differences among all three problem types, with mean RT for unrelated problems faster than true problems, which in turn were faster than related equations in both tasks. Thus, the significant Task × Type interaction reflected differences in the magnitude of the effects of type in the two tasks. Of particular interest is the magnitude of the interference effect in each task. Following Heidekum et al. (2019), we calculated the RT interference effect for each task as a percentage of the mean RT for the unrelated condition, specifically: (Related RT - Unrelated RT) / Unrelated RT × 100. The mean interference effect for picture-word tasks showed that related problems were completed slower 7.123% (SE = .608) compared to unrelated problems, which was smaller than the 14.479% (SE = 1.027) effect in the multiplication task [*t*(201)] = -7.356, *p* < .001, SE = 1.197]. This confirms that participants in this study showed larger interference effects in the multiplication task compared to the picture-word task. This result contrasted with Heidekum et al., who did not find a significant difference in the percentage of RT interference effect between the two tasks (p. 382).

3.2. Task Comparisons: Accuracy (ACC)

We did similar ACC analyses to compare the multiplication and picture-word tasks. The overall accuracy was 80.171% for the multiplication task and 89.800% for the picture-word task. Mean ACC as a function of task and problem type is also shown in Table 1. A similar pattern of observation was found in the ACC analysis. There was a main effect of task, *F*(1, 201) = 188.823, *p* < .001, η_p^2 = .484, indicating lower mean ACC for multiplication (*M* = 80.171, *SE* = .740) than the picture-word task (*M* = 89.800, *SE* = .440). There was also a main effect of problem type, *F*(1.510, 303.498) = 225.042, *p* < .001, η_p^2= .528, showing that participants have lower ACC in completing related problem (*M* = 80.184, *SE* = .588), followed by true (*M* = 82.680, *SE* = .717) and unrelated problem types (*M* = 92.091, *SE* = .484) (*p* < .001 for all pairwise comparisons). The Task × Type interaction was found in the ACC analysis [*F*(1.815, 364.849) = 4.736, *p* = .012, η_p^2= .023]. Again, the problem types for the two tasks were analyzed separately to investigate the interaction effect. For the picture-word task (see Table 1), the main effect of type [*F*(1.767, 355.166) = 160.398, *p* < .001, η_p^2 = .444] indicated that participants had higher ACC for unrelated problems (*M* = 96.132, *SE* = .409) compared to the true (*M* = 87.500, *SE* = .676) and related problems (*M* = 85.767, *SE* = .584) (*p* = .051 for true vs. related, *p* < .001 for all other pairwise comparisons). An effect of type in the multiplication task was also confirmed [*F*(1.576, 316.787) = 120.273, *p* < .001, η_p^2 = .374], of which the unrelated problems had the highest ACC (*M* = 88.050, *SE* = .759) followed by true (*M* = 77.860, *SE* = 1.028) and related: (*M* = 74.691 , *SE* = .908); (*p* < .001 for all pairwise comparisons among problem types for the multiplication task).

The ACC interference effect was calculated for each task as a percentage of the mean ACC for the unrelated condition by using (Unrelated ACC – Related ACC) / Unrelated ACC × 100. In this analysis, the interference effects are expressed by a positive mean percentage (i.e., lower accuracy in the related than unrelated problem condition). The mean interference effects for picture-word tasks suggested that unrelated problems were less error-prone 10.663% (SE = .569) than related problems. This interference effect was smaller than the one shown in multiplication (*M* = 15.153%, SE = .803), meaning larger interference effects in the multiplication task compared to the picture-word task. [*t*(201)] = -4.489, p < .001, SE = .994].

3.3. Correlations Among Personality Components

Before analyzing the correlations related to our dependent performance measures, the current study first tested reliability and correlations for the components within BFI-II to check if the present sample was typical to show Big Five personality characteristics. The BFI-II scale contained five subscales, each consisting of 12 items. Results from reliability tests showed we found good internal consistency for the negative emotionality subscale (α = .869), open-mindedness subscale (α = .821) and conscientiousness subscale (α = .801). The internal consistency for the other two subscales was also acceptable, with Cronbach’s Alpha equaling .741 for the extraversion subscale and .702 for the agreeableness subscale. The current study then conducted a correlational analysis between these five subscales, and the results are shown in Table 2.

Table 2. Correlations among the five personality components of BFI-II

	(1)	(2)	(3)	(4)	(5)
(1) Extraversion	--				
(2) Agreeableness	0.041	--			
(3) Conscientiousness	$.359^{**}$	$.316^{**}$	--		
(4) Negative Emotionality	$-.378^{**}$	$-.172^{*}$	$-.312^{**}$	--	
(5) Open-Mindedness	$.173^{*}$	$.395^{**}$	$.390^{**}$	-0.074	--

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

We replicated previous research (Soto & John, 2017) about the positive correlations between extraversion and conscientiousness [$r(199) = .359$, $p <.001$], extraversion and open-mindedness [$r(199) = .173$, $p = .014$], agreeableness and conscientiousness [$r(199) = .316$, $p < .001$], agreeableness and open-mindedness [$r(199) = .395$, $p < .001$], and conscientiousness and open-mindedness [$r(199) = .390$, $p < .001$]. We also replicated the negative correlations between extraversion and negative emotionality [$r(199) = -.378$, $p < .001$], agreeableness and negative emotionality [$r(199) = -.172$, $p = .015$] and conscientiousness and negative emotionality [$r(199) = -.312$, $p < .001$]. Contrary to Soto and John (2017), the positive correlations between extraversion and agreeableness [$r(199) = .041$, $p = .567$] and the negative correlations between negative emotionality and open-mindedness [$r(199) = -.074$, $p = .298$] were not significant. With these exceptions, the BFI-II correlations in the current study matched the personality characteristics pattern found in the past literature and thus could be further analyzed and interpreted.

3.4. Predictors of Dependent Performance Measures

Before going into depth with dependent performance measures, the current study first identified predictors influencing participants' performance in both tasks (see Table 3). The predictors included working memory capacity (WM Digit Span), math anxiety, negative emotionality (including anxiety and close-related constructs), insecure attachment (Attachment Anxiety and Attachment Avoidance), and secure attachment (Attachment Security).

Table 3. Descriptive Statistics for Predictor Variables

	N	Minimum	Maximum	Mean	Mean Std. Error	Std. Deviation
WM Digit Span	201	2	8	4.95	0.099	1.401
Math Anxiety	201	0.04	3.84	1.8167	0.05688	0.80634
Negative Emotionality	201	1.00	4.92	3.1491	0.05172	0.73330
Attachment Anxiety	201	1.00	6.83	3.7246	0.09205	1.30504
Attachment Avoidance	201	1.00	6.33	3.0489	0.07555	1.07107
Attachment Security	200	2.00	5.95	4.3857	0.04834	0.68363
Valid N (listwise)	198					

We also conducted reliability tests to check the internal consistency of the scales. The reliability tests suggested that we found excellent internal consistency for the 25-item math anxiety scale (α = .943), 18-item attachment anxiety subscale (α = .936), and 18-item attachment avoidance subscale (α = .932). For exploration, we also conducted reliability tests for subscales of attachment security; we found excellent internal consistency for the 14-item sense of support and respect scale (α = .923), good internal consistency for the 7-item emotional awareness subscale (α = .867), 7-item emotional regulation capacity subscale (α = .835), and acceptable internal consistency for the 2-item attunement to other's emotion subscale (α = .767).

3.5. Predictors of Absolute Performance

As one of our dependent performance measures, we first examined absolute performance for both tasks, a measure of RT and ACC performance on the true problems that did not contribute to separate analyses of memory interference (i.e., related vs. unrelated problems). Note that the number of participants per test varies between 202 to 199 in the following correlation analyses owing to a small number of empty cells; thus, the degrees of freedom for these analyses vary slightly. Among all predictors, we first examined whether working memory digit span and math anxiety were predictive of participants' absolute RT and ACC performance in both tasks. Correlation results are shown in Table 4. Absolute performance on the two tasks was positively correlated for each dependent measure, with $r(200) = .367$ for RT and $r(200) = .388$ for ACC (both $p < .001$), indicating that good performance on one interference task predicted good performance on the other. Nonetheless, participants who were fast at responding to picture-word problems tended to have higher ACC in the multiplication task [$r(200) = -.185$, $p = .008$].

Table 4. Correlations between absolute performance, working memory, and math anxiety

	(1)	(2)	(3)	(4)	(5)	(6)
(1) M True RT	--					
(2) PW True RT	$.367^{**}$	--				
(3) M True ACC	-0.025	$-.185^{**}$	--			
(4) PW True ACC	0.125	-0.111	$.388^{**}$	--		
(5) WM Digit Span	$-.226^{**}$	-0.108	$.334^{**}$	0.085	--	
(6) Math Anxiety	$.151^{*}$	-0.006	$-.192^{**}$	$-.154^{*}$	$-.151^{*}$	--

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Results about working memory revealed a negative correlation between working memory digit span and multiplication RT [*r*(199) = -.226, *p* = .001] and a positive relationship between working memory span with multiplication ACC [*r*(199) = .334, *p* <.001]. This replicated the previous literature on how working memory influences math performance (e.g., Ashcraft & Kirk, 2001); specifically, as working memory span increased, arithmetic ACC tended to increase, and arithmetic RT tended to decrease. In contrast, picture-word RT and accuracy were not significantly correlated with working memory [RT: *r*(199) = -.108, *p* = .126; ACC: *r*(199) = .085, *p* = .233].

As Table 4 shows, the current study also replicated the relationship between working memory and math anxiety [*r*(198) = -.151, *p* = .032] (Bosmans & De Smedt, 2015), supporting the “worry account” that worries and intrusive thoughts deplete limited working memory resources for those high math anxious participants (Ashcraft & Kirk, 2001).

In terms of math anxiety and verification task performance, we replicated the previous research (e.g., Faust, 1996; Ashcraft & Kirk, 2001) that showed math anxiety was positively correlated with multiplication RT [*r*(199) = .151, *p* = .032] and negatively correlated with multiplication ACC [*r*(199) = -.192, *p* = .006]. Thus, higher math anxiety was associated with relatively poor multiplication performance. Interestingly, however, we found a negative correlation between math anxiety and picture-word ACC [*r*(199) = -.154, *p* = .029], which suggests that higher levels of math anxiety also were associated with lower picture-word verification accuracy.

To further clarify how working memory and math anxiety plays a role in absolute performance, the current study conducted two multiple regression analyses. The first multiple regression analysis was calculated to predict working memory digit span based on the absolute performance for both tasks and performance measures (see Table 5 for coefficients). The four verification task predictors entered the equation simultaneously, which allowed us to assess their unique prediction of working memory span with common variance removed. A significant regression equation was found *F*(4, 196) = 9.348, p < .001, with an adjusted R^2 = .143. The results confirmed that multiplication RT ($t = -3.204$, $p = .002$) and ACC ($t = 4.738$, $p < .001$) were both independent predictors of working memory digit span but the picture-word task measures did not predict unique WM variance (RT: $t = .544$, $p = .587$; ACC: $t = -.212$, $p = .833$).

Table 5. Multiple regression with working memory digit span as the dependent variable

		Unstandardized Coefficients		Standardized Coefficients		
	Model	B	Std. Error	Beta	t	Sig.
1	(Constant)	3.744	1.058		3.539	0.001
	M True RT	-0.001	0.000	-0.229	-3.204	0.002
	M True ACC	0.033	0.007	0.341	4.738	<0.001
	PW True RT	0.000	0.001	0.039	0.544	0.587
	PW True ACC	-0.002	0.011	-0.015	-0.212	0.833

a. Dependent Variable: WM Digit Span

The second multiple regression analysis was performed using math anxiety as the dependent variable and the absolute performance for both interference tasks as predictors (see Table 6 for coefficients). A significant regression equation was found $F(4, 196) = 4.451$, $p = .002$, with an adjusted $R^2 = .065$. The coefficient results confirmed that math anxiety was a predictor for multiplication RT ($t = 2.814$, $p = .005$) and ACC ($t = -2.105$, $p = .037$), but the result didn’t confirm the relationship between math anxiety and picture-word absolute performance [RT: $t = -1.693$, $p = .092$; ACC: $t = -1. 759$, $p = .080$].

Table 6. Multiple regression with math anxiety as the dependent variable

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	3.241	0.636		5.098	<0.001
	M True RT	0.001	0.000	0.210	2.814	0.005
	M True ACC	-0.009	0.004	-0.158	-2.105	0.037
	PW True RT	-0.001	0.000	-0.128	-1.693	0.092
	PW True ACC	-0.011	0.006	-0.133	-1.759	0.080

Dependent Variable: Math Anxiety

So far, for absolute measures of interference-task performance, working memory digit span and math anxiety were identified as predictors that specifically related to multiplication absolute performance in terms of RT and ACC, and these two measures were not predictive of the performance of the picture-word task. However, it is not clear whether they predict independent variability in absolute performance. Because working memory digit span and math anxiety were significantly correlated, it is possible that their separate significant correlations with absolute performance might actually be shared variance. To further examine, we conducted more multiple regression analyses using absolute multiplication performance (RT and ACC) as dependent variables and math anxiety and working memory digit span as predictors.

Table 7. Multiple regression with multiplication absolute RT as the dependent variable

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	1320.671	85.042		15.530	<0.001
	WM Digit Span	-39.590	13.246	-0.208	-2.989	0.003
	Math Anxiety	39.581	23.273	0.119	1.701	0.091
Dependent Variable: M True RT						

For multiplication absolute RT (see Table 7 for coefficients), a significant regression equation was found *F*(2, 197) = 6.838, p = .001, with a the adjusted $R^2 = .055$; The coefficient results confirmed that working memory digit span was an independent predictor for multiplication absolute RT (*t* = -2.989, *p* = .003), but math anxiety was not (*t* = 1. 701, *p* = .091). This result indicated that the correlation between math anxiety and multiplication absolute RT could be mediated by its shared variance with working memory (i.e., digit span), so math anxiety was not unambiguously a direct contributor to the multiplication absolute RT performance. Nonetheless, the results were potentially consistent with the “worry account” that worries and intrusive thoughts about math deplete the working memory resources for those math-anxious participants, thus making them difficult to perform well on math tasks (Ashcraft & Kirk, 2001).

Table 8. Multiple regression with multiplication absolute ACC as the dependent variable

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	67.101	4.484		14.966	<0.001
	WM Digit Span	3.231	0.698	0.310	4.627	<0.001
	Math Anxiety	-2.925	1.227	-0.160	-2.384	0.018

Dependent Variable: M True ACC

For multiplication absolute ACC (see Table 8 for coefficients), we found a significant regression equation *F*(2, 197) = 15.571, p < .001, with a the adjusted $R^2 = .128$; Again, the coefficient results confirmed that working memory digit span was an independent predictor for multiplication absolute ACC (*t* = 4.627, *p* < .001). Interestingly, unlike the regression analysis for absolute multiplication RT, we also found math anxiety independently predictive of multiplication absolute ACC (*t* = -2.384, *p* = .018).

Overall, we found that working memory digit span and math anxiety were predictive for absolute multiplication performance, of which working memory digit span independently predicted both absolute multiplication RT and ACC performance. In contrast, math anxiety independently predicted only absolute multiplication ACC performance. Except for these two predictors, the current study also explored whether other predictors (negative emotionality and attachment) influence people’s absolute performance on both tasks.

Table 9. Correlations between absolute performance, negative emotionality, and attachment

	M True RT	PW True RT	M True ACC	PW True ACC
Negative Emotionality	-0.088	0.003	0.084	0.039
Attachment Anxiety	0.056	0.048	0.030	0.008
Attachment Avoidance	0.095	0.100	0.054	-0.077
Attachment Security	-0.052	-0.062	0.005	0.119

**. Correlation is significant at the 0.01 level (2-tailed).

Table 9 shows the relationships between the absolute performance of the two tasks and negative emotionality and attachment measures. Negative emotionality was not correlated with absolute multiplication or picture-word performance.[1] We also did not find any correlation between insecure attachment measures (attachment anxiety, attachment avoidance) and people’s absolute performance (RT and ACC) in either task. These results suggested that the negative emotionality and attachment measures could not predict multiplication and picture-word absolute performance.

In addition, the current study investigated the relationship between each predictor. Table 10 shows the correlations among working memory digit span, math anxiety, negative emotionality, attachment anxiety, attachment avoidance, and attachment security.

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[1] Anxiety facet (4-item) of negative emotionality scale was also not correlated with absolute multiplication [RT: *r*(199) = -.041, *p* = .560; ACC: *r*(199) = .021, *p* = .773]or picture-word performance[RT: *r*(199) = .048, *p* = .499; ACC: *r*(199) = .029, *p* = .680].

Table 10. Correlations between working memory, math anxiety, and other predictors

	(1)	(2)	(3)	(4)	(5)	(6)
(1) WM Digit Span	--					
(2) Math Anxiety	-.151*	--				
(3) Negative Emotionality	.147*	0.100	--			
(4) Attachment Anxiety	-0.085	.189**	.332**	--		
(5) Attachment Avoidance	-0.035	0.029	0.079	.390**	--	
(6) Attachment Security	0.013	-0.132	-.328**	-.497**	-.604**	--

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

As Table 10 shows, there was a positive correlation between working memory digit span and negative emotionality [*r*(198) = .147, *p* = .037][2], suggesting that participants with low working memory capacity tend to be less anxious in general. Because the working memory measure in the current study was math-specific (numbers and digits as stimuli), to some extent, this positive correlation indicated that the role of working memory capacity is more general than specific. Math anxiety was positively correlated with attachment anxiety [*r*(199) = .189, *p* = .007], supporting the idea that insecure attachment potentially is an underlying origin of math anxiety (Bosmans & De Smedt, 2015). As an non-math-related anxiety measure, negative emotionality was positively correlated with attachment anxiety [*r*(198) = .332, *p* < .001], and it was negatively related to attachment security [*r*(197) = -.328, *p* < .001][3]. Results about attachment showed the positive correlation between attachment anxiety and attachment avoidance [*r*(199) = .390, *p* < .001]. The results also showed the negative correlations between

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[2] No correlation between anxiety facet of negative emotionality scale and working memory digit span [*r*(198) = .126, *p* = .077], but significant correlation between anxiety facet and math anxiety [*r*(198) = .160, *p* = .024].

[3] Same direction of correlation was found between anxiety facet of negative emotionality scale and attachment [attachment anxiety: *r*(198) = .165, *p* = .020; attachment security: *r*(197) = -.156, *p* = .028].

attachment anxiety and attachment security [*r*(198) = -.497, *p* < .001], and the correlations between attachment avoidance and attachment security [*r*(199) = -.604, *p* < .001].

In brief, absolute performance results identified working memory digit span as an independent predictor for the absolute performance of multiplication tasks in terms of RT and ACC. Math anxiety was not directly contributing to the absolute multiplication RT performance, but it was predictive independently for the absolute multiplication ACC. Both working memory digit span and math anxiety were not predictive of the absolute performance of the picture-word task, indicating the specificity of math performance. Furthermore, we found no relation between people's absolute performance and other predictors such as negative emotionality, attachment anxiety, attachment avoidance and attachment security. This indicates that these anxiety-related and attachment measures did not relate to people's absolute performance on both tasks.

3.6. Predictors of the Verification Interference Effect

Apart from absolute performance, the current study analyzed the memory interference measures as another dependent performance measure. The memory interference effect is the percentage of cost in RT and ACC on related problems type relative to unrelated problems. Similar to what we did with absolute performance analysis, we first explored whether working memory digit span and math anxiety were predictive of people's memory interference effects (see Table 11).

In contrast to the absolute performance (Table 4), no significant correlation was found between multiplication and picture-word RT and ACC interference measures. In addition, working memory digit span was not correlated with any interference effect measures for the two tasks. We also did not find correlations between math anxiety and interference effect measures. These results suggested that neither working memory digit span nor math anxiety were predictors for participants' memory interference effects on RT and ACC in both multiplication and picture-word tasks.

Table 11. Correlations between interference measures, working memory, and math anxiety

	(1)	(2)	(3)	(4)	(5)	(6)
(1) M RT Interference	--					
(2) PW RT Interference	-0.006	--				
(3) M ACC Interference	-0.122	0.056	--			
(4) PW ACC Interference	0.061	-0.115	-0.021	--		
(5) WM Digit Span	-0.044	0.062	-0.130	-0.109	--	
(6) Math Anxiety	-0.121	-0.054	0.105	0.023	-.151*	--

*. Correlation is significant at the 0.05 level (2-tailed).

The current study then explored whether other predictors (negative emotionality and attachment) influenced people's memory interference effects. Table 12 shows the correlation between the interference effect, negative emotionality, and attachment (attachment anxiety, attachment avoidance, and attachment security). Similar to absolute performance (Table 9), none of the negative emotionality[4] and insecure attachment predictors (attachment anxiety, attachment avoidance) were predictive for participants' memory interference in RT and ACC in both tasks. However, in contrast to absolute performance (Table 9), attachment security was found to be the only significant predictor of the memory interference measures. It was predictive for the RT interference effect for both tasks, with *r*(198) = -.170, *p* = .016 for multiplication RT interference and *r*(198) = -.151, *p* = .033 for picture-word RT interference. Even though it was not a predictor for the participants' absolute performance measures, this result raised the possibility that the more securely attached participants were associated with lower memory interference in both multiplication and picture-word tasks.

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[4] Anxiety facet of negative emotionality scale was also not correlated with interference multiplication [RT: *r*(199) = .128, *p* = .069; ACC: *r*(199) = -.066, *p* = .355]or picture-word performance[RT: *r*(199) = -.034, *p* = .628; ACC: *r*(199) = -.022, *p* = .759].

Table 12. Correlations between interference measures, negative emotionality, and attachment

	M RT Interference	PW RT Interference	M ACC Interference	PW ACC Interference
Negative Emotionality	0.106	0.034	-0.026	-0.032
Attachment Anxiety	0.034	-0.021	0.105	0.072
Attachment Avoidance	0.072	0.109	-0.005	-0.043
Attachment Security	-.170*	-.151*	0.061	0.021

*. Correlation is significant at the 0.05 level (2-tailed).

4. General Discussion

The current study successfully replicated the previous findings (Ashcraft & Faust, 1994; Ashcraft & Kirt, 2001) on how working memory capacity and math anxiety were predictive for math performance, but not picture-word performance. Specifically, high working memory capacity (high scores on working memory digit span task) was associated with low absolute multiplication RT and high absolute multiplication ACC. On the other hand, math anxiety was not directly contributing to absolute multiplication RT, but it correlated with absolute multiplication ACC, in which higher math-anxious individuals completed multiplication problems with lower ACC. This result provided some evidence that working memory played a role in the relationship between math anxiety and math performance (Ashcraft & Kirk, 2001). As such, the results are consistent with Ashcraft's "worry" account that worries and intrusive thoughts about math deplete the working memory resources of those math-anxious participants and limit their performance on the math task at hand. The study also replicated that insecure attachment (especially attachment anxiety) was correlated with math anxiety (Bosmans & De Smedt, 2015). There was no correlation between math anxiety and negative emotionality, but the anxiety facet of the negative emotionality scale was positively correlated with math anxiety. In addition, attachment security was found as the only predictor for people's memory RT interference effect on both tasks.

Of course, our primary focus was findings about absolute verification-task performance and memory interference effects in those tasks. In line with Heidekum et al. (2019), we found a significant memory interference effect in both the multiplication and picture-word tasks. Specifically, the interference effects were quantified by differences in RT and ACC, in which participants completed related problems with longer RT and lower ACC compared to the unrelated problems in both tasks. Potential explanations for these interference effects in multiplication could be traced back to Campbell (1987), who suggested there was a response competition that occurred after the related false answer was activated. Related equations (e.g., 8

× 4 = 24) typically would produce more robust competitive memory activation because they involved more common features or semantic associations (8 × 3 = 24 and 6 × 4 = 24) than an unrelated equation (8 × 4 = 27). Consequently, a related equation produces strong illusory familiarity or interferes with the retrieval of the correct answer for comparison to the presented false answer. An analogous mechanism could mediate interference in the picture-word task. When the picture and the word came from the same semantic category, the shared categorical memory activation could produce an illusory sense of familiarity consistent with a matched picture-word pair compared to unrelated picture-word pairs.

In the present study, working memory predicted absolute multiplication performance but not picture-word performance (Table 5). Specifically, better multiplication performance was associated with a higher working memory span. This is potentially consistent with De Visschers and Noël’s (2014) proposal that individual differences in multiplication memory performance are partly explained by differences in the quality of working memory encoding processes during multiplication development. Specifically, problems that share features (e.g., a common multiplier such as 3 × 8 and 4 × 8) may not be encoded distinctly in working memory, which limits their discriminability during subsequent retrieval from long-term memory. Thus, limits in working memory yield associative interference in the long-term retrieval of multiplication facts.

While working memory digit span was predictive of absolute multiplication performance, it was not correlated with the multiplication interference effects. This dissociation implies that multiplication interference per se was not dependent on working memory capacity and therefore, not a function of cognitive resource limitations. This result seems problematic for the De Visschers and Noël (2014) account, which presumably would predict a strong link between working memory efficiency and related-product interference in the multiplication verification task.

Moreover, although both absolute RT and accuracy for true equations were significantly correlated (Table 4), the multiplication interference effect was not correlated with the picture-word interference effect (Table 11). This might lead one to conclude that the two interference effects are simply unrelated to each other. In contrast, however, attachment security was negatively correlated (Table 12) with the RT interference effect in both the multiplication (-.170) and picture word tasks (-.151). These results suggest that the more securely attached individuals were less susceptible to memory interference in both the multiplication and picture-word tasks. Although these significant correlations are relatively small, it would be worthwhile to pursue these intriguing results.

The present study and Heidekum et al. found significant differences in RT and ACC in both tasks regarding the related and unrelated problems. However, the two studies found different response patterns in terms of problem types in the two tasks. Specifically, in the current study, the Task × Type RT results revealed that participants completed unrelated problems the fastest, followed by true and related problems, and this response pattern was comparable in both multiplication and picture-word tasks. However, Heidekum et al. found a different pattern in the multiplication task, in which participants completed true multiplication problems with the best RT performance, followed by unrelated and related problems. Moreover, the current study found Task × Type interaction in the ACC analysis, in which participants completed the related picture-word problems with the lowest ACC compared to unrelated problems. No significant differences were found between the true and related picture-word problems. Participants completed the related multiplication problems with the lowest ACC, followed by the true and related multiplication problems. Again, these interaction results differed from Heidekum et al., who did not find significant Task × Type interaction in the ACC analysis.

The discrepancies found between the current and Heidekum et al.’s (2019) study on RT and ACC response patterns lead to the question of exploring the possible reasons that contribute to the better performance for unrelated compared to true problems. One potentially important difference in the design of the Heidekum et al. multiplication task and the present study was the types of unrelated answers used. Specifically, their unrelated false answers were not products of any one-digit × one-digit multiplication problem and often involved prime numbers (e.g. 5 × 2 =

17, 4 × 4 = 13). In contrast, unrelated answers in the present study always involved answers to other one-digit × one-digit multiplication problems (3 × 7 = 25, 2 × 8 = 15) and were correct answers for other problems in true equations (5 × 5 = 25, 3 × 5 = 15) . Within-experiment practice with true equations could make their products relatively easy to reject as false in the context of unrelated equations. It is important to point out that using unrelated answers that are one-digit × one-digit products for other problems isolates any observed performance difference between unrelated and related equations to the effect of related answers being multiplicatively related to at least one of the problem operands (e.g., 3 × 7 = 27, 3 × 5 = 25). In contrast, the Heidekum related vs. unrelated stimuli only distinguish between simple multiplication products vs. non-products and does not isolate relatedness per se. This could explain why unrelated stimuli in the present experiment were relatively fast and accurate relative to the other conditions and in comparison to the Heidekum experiment.

Another potential reason for the difference in unrelated vs. true performance could be attributed to the different ratios of true and false conditions in Heidekum et al. and the current study. In Heidekum et al., both multiplication and picture-word tasks, the ratio of the true and false (related, unrelated) problems was 1:1. However, in the present study, the false problems accounted for two-thirds of the total problems in both tasks (i.e., there were equal numbers of related, false, unrelated false, and true equations). This could lead participants to be more adapted to or primed to make a “false” response choice. The bias of pressing the “false” key could give an RT advantage with relatively higher accuracy for the unrelated problems relative to true problems. This bias would also have influenced the related problems, but they were slower with lower accuracy compared to the unrelated problems due to the memory interference lure.

Furthermore, the current study found larger memory interference on RT and ACC in the multiplication task relative to the picture-word task. These results were in contradiction to no significant difference between the size of the interference effects in both tasks found in Heidekum et al. (2019). As the unrelated condition is the baseline for calculating the size of interference effects, the relatively fast and accurate unrelated multiplication condition in the present study would translate into a relatively larger interference effect. Thus, again, differences in the composition of the stimuli for the multiplication task might explain the differences between the present results and those of Heidekum et al.

An important potential limitation of the present experiment concerns the fixed order of tasks, in which participants always completed the memory interference tasks first, followed by the working memory capacity task, and the questionnaires at the end. The performance of the working memory capacity task could be influenced because participants had already put cognitive efforts into completing the two memory interference tasks. Hence, they might develop cognitive fatigue that reduces potential resources to complete the working memory digit span task. Similarly, participants' fatigue might also influence the questionnaires' performance. Nonetheless, counterbalancing the order of the interference and questionnaire tasks would be preferable but would require a sample size that is not practical for the present investigation.

5. Conclusions

In summary, the present experiment found that working memory capacity and math anxiety predicted math performance but not picture word performance. There was some evidence that working memory differences contributed to the relationship between math anxiety and math performance. In addition, participants showed considerable memory interference effects in multiplication and picture-word tasks in terms of response time and accuracy, and this effect was found to be larger in the multiplication task than in the picture-word task. In contrast to absolute math performance, the multiplication interference effect did not vary with working memory or math anxiety measures, but attachment security was positively related to both multiplication and picture-word task interference.

Taken collectively, the results of the current study imply some degree of independence between predictors of absolute math (i.e., multiplication verification) and associative interference effects in multiplication retrieval. However, it is not immediately clear how to reconcile these findings with the view that susceptibility to interference contributes substantially to individual differences in multiplication skill development and subsequent adult performance (De Visscher & Noël, 2013; 2014). The present study made new inroads to explore predictors contributing to individual differences in people's arithmetic fact storage in long-term memory, but it remains for future research to continue exploring how developmental, personality and cognitive constructs collectively influence people's memory processes for arithmetic.

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Appendix A

Math Interference Task Stimuli

Problem		Answer	
	Correct	Related	Unrelated
2 × 2	4	8	9
2 × 3	6	12	13
2 × 4	8	16	15
2 × 5	10	25	21
2 × 6	12	16	15
2 × 7	14	21	25
2 × 8	16	18	15
2 × 9	18	27	25
3 × 3	9	6	8
3 × 4	12	24	30
3 × 5	15	25	28
3 × 6	18	24	35
3 × 7	21	27	25
3 × 8	24	18	14
3 × 9	27	18	32
4 × 4	16	8	6
4 × 5	20	15	14
4 × 6	24	28	25
4 × 7	28	21	27
4 × 8	32	24	27
4 × 9	36	45	42
5 × 5	25	20	21
5 × 6	30	35	32
5 × 7	35	45	27
5 × 8	40	45	42
5 × 9	45	40	49
6 × 6	36	12	16
6 × 7	42	63	64
6 × 8	48	72	63
6 × 9	54	63	64
7 × 7	49	42	45
7 × 8	56	42	36
7 × 9	63	56	48
8 × 8	64	72	54
8 × 9	72	63	49
9 × 9	81	54	49

Appendix B

Picture-word Interference Task Stimuli

ImageStim	WordStim		
	Correct	Related	Unrelated
dog.jpg	dog	cat	glass
cow.jpg	cow	horse	comb
lion.jpg	lion	tiger	bowl
swan.jpg	swan	duck	scissors
eagle.jpg	eagle	owl	horse
bee.jpg	bee	fly	cat
flower.jpg	flower	leaf	tiger
apple.jpg	apple	pear	leaf
pliers.jpg	pliers	scissors	crown
crown.jpg	crown	hat	chain
chain.jpg	chain	lock	shoe
cup.jpg	cup	glass	pan
pan.jpg	pan	bowl	flower
knife.jpg	knife	spoon	cow
shoe.jpg	shoe	boot	eagle
brush.jpg	brush	comb	swan
cat.jpg	cat	lion	boot
horse.jpg	horse	eagle	lock
tiger.jpg	tiger	swan	spoon
duck.jpg	duck	cow	hat
owl.jpg	owl	dog	fly
fly.jpg	fly	bee	duck
leaf.jpg	leaf	flower	pear
pear.jpg	pear	apple	owl
scissors.jpg	scissors	chain	cup
hat.jpg	hat	shoe	knife
lock.jpg	lock	pliers	pliers
glass.jpg	glass	pan	brush
bowl.jpg	bowl	cup	apple
spoon.jpg	spoon	brush	lion
boot.jpg	boot	crown	bee
comb.jpg	comb	knife	dog