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The relationship between math anxiety and math performance: The moderating role of visuospatial working memory

Alessandro Cuder, Marija Živković, Eleonora Doz, Sandra Pellizzoni *, Maria Chiara Passolunghi

Department of Life Sciences, University of Trieste, 34128 Trieste, Italy

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ABSTRACT

According to the processing efficiency theory (PET), math anxiety would interfere with working memory resources, negatively affecting mathematical abilities. To date, few studies have explored how the interaction between math anxiety and working memory would affect different types of math tasks, especially in primary school children. Therefore, the purpose of this study was to explore whether the interplay between math anxiety and working memory would influence performance in numerical operations (i.e., math fluency task) and mathematical reasoning (i.e., math reasoning task) in a group of primary school children (N = 202). Results showed that visuospatial working memory appeared to moderate the relationship between math anxiety and math performance when the math fluency task was considered, indicating that participants with higher levels of working memory were more negatively affected by math anxiety. No interaction effect was found for the math reasoning task in which students' scores were explained only by visuospatial working memory. The findings suggest that math anxiety and visuospatial working memory interact to influence performance in the math fluency task and that this effect may vary depending on the strategies used to complete the task. On the other hand, results on the math reasoning task showed that visuospatial working memory continues to have a positive effect on the math performance independently of math anxiety. The implications in the educational setting are discussed, pointing to the

* Corresponding author.
E-mail address: spellizzoni@units.it (S. Pellizzoni).

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importance of monitoring and intervention studies on affective factors.

Introduction

In an increasingly number-based society, mathematical skills are essential for individuals' development at a personal level (Furlong et al., 2016; Gross et al., 2009), academic and occupational levels (Bynner, 1997; Dougherty, 2003; Gerardi et al., 2013; Gross et al., 2009; Rivera-Batiz, 1992), but also at collective and social levels (Foley et al., 2017; Pellizzoni et al., 2020; Peterson et al., 2011). Furthermore, national and international reports show that 36% of students struggle to achieve the basic level of math proficiency and 31% of students report negative emotions toward math activities (Organization for Economic Cooperation and Development [OECD], 2013). Given the importance of these abilities, researchers are now focusing on understanding the predictive role of the factors involved in math achievement (Fonteyne et al., 2017; Higbee & Thomas, 1999; Lu et al., 2011). The literature has extensively investigated the cognitive abilities (general cognitive precursors) that prompt math learning, including working memory (WM) that has been widely researched in the field (Fuchs et al., 2010; Passolunghi et al., 2014). Similarly, other studies have evaluated the contribution of emotional factors (e.g., general or specific anxiety) to math performance (e.g., Dowker et al., 2016). Nonetheless, few studies have focused on the mutual influence of cognitive and emotional factors in determining math proficiency, particularly in young children (Cargnelutti et al., 2017; Justicia-Galiano et al., 2017; Lee et al., 2014; Pellizzoni et al., 2022; Živković et al., 2022).

In light of the developmental sample, this study could be considered one of the first attempts to explore the unique contribution of emotional and cognitive factors, as well as their interaction, in predicting math learning. In particular, we evaluated how diverse visuospatial working memory (VSWM) profiles would be affected by math anxiety (MA) on arithmetic operations (i.e., numerical skills involving number knowledge, numerical manipulations, and mental arithmetic; Geary et al., 2007) and mathematical reasoning (i.e., performing inferences, deductions, inductions, and associations in the domain of numerical knowledge; Thompson, 1996). In doing so, we evaluated which group of children is most susceptible to VSWM disruption as a result of a high level of MA, disambiguating between different models proposed in the adult literature (Ashcraft & Kirk, 2001; Beilock & Carr, 2005) and providing important insight into math learning and education.

Affective and cognitive factors and their interplay in the learning process

The role of emotional and cognitive factors in mathematical learning has been extensively studied in the literature, with a particular emphasis on their distinct impacts on learning (e.g., De Smedt et al., 2009; Donolato et al., 2020; Maehler & Schuchardt, 2016; Sorvo et al., 2022; Wu et al., 2012). Concerning emotional factors, several studies have highlighted the important role of math anxiety (Caviola et al., 2022; Namkung et al., 2019; Zhang et al., 2019).

Math anxiety

MA has several definitions that underpin different understandings of the construct, ranging from a personality trait to a clinical condition (Cipora et al., 2022). According to Richardson and Suinn (1972), MA is defined as a feeling of tension and anxiety that interferes with the manipulation of numbers and the solving of mathematical problems in ordinary life and academic situations. In this context, MA refers to a trait or state attitude that varies between individuals, resulting in avoidant behavior, less practice and competence, underachievement, and disruption of cognitive resources needed to accomplish the tasks (Cipora et al., 2022; Van Ameringen et al., 2003; Woodward & Fergusson, 2001). According to meta-analytic evidence, MA has a moderately negative effect on mathematical performance (ranging from $r = -.34$ to $r = -.32$) and starts to take root early in childhood (Caviola et al., 2022; Namkung et al., 2019; Zhang et al., 2019). Although the association between MA and math achievements is well established, it is not clear whether MA is a cause or consequence of math underachievement (Carey et al., 2016; Cohen & Rubinsten, 2021; Rubinsten et al., 2018). In 77% of cases, children with severe MA have typical or better mathematics performance (Devine et al., 2018). These data suggest that other factors besides MA should be taken into account when considering math difficulties and that the cognitive and emotional problems related to mathematics are largely dissociated (Devine et al., 2018). Therefore, considering cognitive aspects could help to clarify the role of affective factors and their complex interaction in math learning.

Working memory

Within general cognitive precursors, WM has a prime role in predicting math achievement (Berg, 2008; Bull et al., 2008; De Smedt et al., 2009; Gathercole et al., 2004; Giofrè et al., 2017). WM is defined as a limited capacity system that holds information for brief periods of time while processing it (Baddeley & Hitch, 1974). The most popular theorization is the tripartite model of WM that is composed of a central executive responsible for data storage, processing, and monitoring and two modality-dependent systems that handle verbal working memory (VWM) and VSWM information (Baddeley & Hitch, 1974; Gathercole et al., 2004; Giofrè et al., 2017). WM has a well-established positive effect on a variety of math domains (Caviola et al., 2014; Giofrè et al., 2013, 2014; Mammarella et al., 2013; Passolunghi et al., 2019; Passolunghi & Mammarella, 2010). Furthermore, there is ample evidence that children with a higher WM capacity have an advantage in mathematics (Friso-van den Bos et al., 2013; Raghubar et al., 2010), whereas those with poor WM are weak in mathematics (Hitch & McAuley, 1991; Passolunghi & Pazzaglia, 2005; Passolunghi & Siegel, 2004; Siegel & Ryan, 1989).

Recently, research has focused on an intriguing debate on the modality-dependent (verbal or visuospatial) component of WM in math learning. Some studies indicated a substantial correlation between the VWM and VSWM domains (Kane et al., 2004), whereas others found this distinction in some ages but not in others (Swanson, 2008). According to recent studies, VWM is more likely to be related to reading attainment, whereas VSWM is more likely to be related to math performance (Giofrè et al., 2018). Furthermore, during primary school the VSWM component is especially important in solving new and complex math tasks (e.g., Ashkenazi et al., 2013; Li & Geary, 2013; Szűcs et al., 2014), acting as a reliable predictor of math performance (Allen & Giofrè, 2021; Liang et al., 2022) and having a similar influence on numerical operations and mathematical reasoning domains (for systematic reviews, see Allen et al., 2019; Alloway et al., 2009; Meyer et al., 2010). Given the above-mentioned evidence, in the current study we decided to focus on the VSWM component, taking into account two tasks involving both numerical operations (i.e., math fluency task) and mathematical reasoning (i.e., math reasoning task).

The interplay between MA and WM

In several studies, MA was described as having a detrimental effect on math achievement by reducing WM resources (Ashcraft & Kirk, 2001; Beilock & Carr, 2005; Beilock & DeCaro, 2007; DeCaro et al., 2010; Miller & Bichsel, 2004; Young et al., 2012). Indeed, it has been suggested that one mechanism by which anxiety would lead to poor math achievement is the disruption of cognitive resources required to complete the task (e.g., Justicia-Galiano et al., 2017; Živković et al., 2022). One explanation for these findings is proposed by the processing efficiency theory (PET; Eysenck & Calvo, 1992). This theory has been developed on Baddeley's model of WM (Baddeley & Hitch, 1974) and suggests that anxiety would interfere with WM resources via intrusive negative thoughts, leading to poor performance effectiveness (i.e., a decrease in performance accuracy) and processing efficiency (i.e., lower task processing speed). In this context, MA would have a detrimental impact on WM resources, causing people to display performances that are more mistake prone and effortful.

Although the impact of the interplay between WM and MA on math learning is well established, it is still not clear whether high- or low-WM capacity individuals would suffer more from the effects of MA (Ramirez et al., 2016; Sidney et al., 2019; Soltanlou et al., 2019). Indeed, there are two main accounts of how MA and WM interact in the context of math learning. According to some studies, low-WM-capacity individuals would suffer more from the negative effects of anxiety because they would have fewer resources to deal with the tasks and the anxious state, whereas high-WM-capacity individuals would have more possibility to simultaneously deal with anxious thoughts and math tasks' requirements (Ashcraft & Kirk, 2001; Miller & Bichsel, 2004; Owens et al., 2008, 2012, 2014; Soltanlou et al., 2019). For instance, Ashcraft and Kirk (2001) found that adults with higher WM were able to manage both math tasks and anxiety-driven thoughts more successfully. Similarly, Miller and Bichsel (2004) found that adults with high MA performed better in calculation and problem solving when they were high in WM. Recently, a study by Soltanlou and colleagues (2019) conducted on primary school children showed that multiplication learning was greatly impaired by MA in students with low VSWM.

In contrast, some studies (Beilock & Carr, 2005; Beilock et al., 2004) observed a phenomenon labeled "choking under pressure." The research indicates that, especially when solving tasks under pressure, people who rely more heavily on WM when solving the math tasks perform worse, whereas people who rely less on WM are less affected by MA (Mattarella-Micke et al., 2011). In this regard, it has been proposed that high-WM individuals who rely more on memory-based math resolution strategies may be hampered by the concurrent presence of MA, resulting in poor mathematical outcomes (Beilock & Carr, 2005). Interestingly, some studies involving young primary school children found that MA negatively affected their math performance on applied problems (Ramirez et al., 2013) and mathematical applications (Vukovic et al., 2013), particularly in those pupils with high levels of WM. Indeed, math tasks, differently from general cognitive ones, necessitate both specific knowledge and strategies that may be depleted by the concurrent presence of MA (Allen et al., 2020; Caviola et al., 2014; Cragg et al., 2017). For instance, in a study by Ramirez and colleagues (2016) that assessed children's math strategies, it was found that students with high WM capacity avoided using advanced WM-consuming strategies when high in MA.

Both these two lines of findings, despite inconsistencies, seem to support the PET given that anxiety would act on an individual's cognitive resources, either by interfering with WM resources (e.g., Soltanlou et al., 2019) or by interfering with correlates of WM, that is, advanced resolution strategies (e.g., Ramirez et al., 2016). Inconsistencies in the literature on the interplay between MA and WM could depend on methodological differences between studies. For example, studies that found those with high levels of WM to be more affected by MA (e.g., Ramirez et al., 2016) employed cross-sectional designs, capturing the impact of affective and cognitive factors on concurrent performance. On the other hand, the study by Soltanlou et al., (2019) assessed the role of these variables in learning, showing that those with lower WM appear to learn less when simultaneously influenced by MA. This could be because participants with higher levels of WM show greater progress in mathematical learning (Tomasetto et al., 2021). Another aspect that might have influenced the results in the literature is the type of task used in the studies. Indeed, recent meta-analyses showed that the variability in results could be partially attributed to the characteristics of the math task (Caviola et al., 2022; Zhang et al., 2019). For instance, performance on arithmetic operations and numerical reasoning tasks, besides being commonly assumed to be two theoretically distinct subdomains of mathematical achievement (Allen et al., 2019; Cornoldi et al., 2020; Wechsler, 2017), also seem to be differentially influenced by affective factors (Caviola et al., 2022; Wu et al., 2017; Zhang et al., 2019; Živković et al., 2022). In particular, performance on school-based tasks such as arithmetic operations may be particularly affected by MA (Ashkenazi & Danan, 2017; Caviola et al., 2022) compared with numerical reasoning tasks (Živković et al., 2022). In addition, it is reported in the literature that greater experience and familiarity with the task may promote the use of more complex strategies (Laski et al., 2014). Thus, in the case of school-based tasks (i.e., arithmetic operations), children may develop advanced solving strategies with more ease than in numerical reasoning tasks, and this may explain some mixed results both between studies (Soltanlou et al., 2019) and within the same study (Vukovic et al., 2013). Assessing these two subdomains of mathematical learning separately would allow us to delve into specific interactions between affective and cognitive aspects, going beyond what cannot be revealed through the use of aggregate assessments (e.g., Ramirez et al., 2013, 2016). Furthermore, even though the PET suggests that anxiety affects both performance accuracy and speed, studies have not examined how the interaction between MA and WM affects timed math tasks. In addition, considering developmental samples, evidence has been gathered from samples of first, second, and third graders (Ramirez et al., 2013, 2016; Vukovic et al., 2013), whereas the last years of primary school are rather underexplored (Soltanlou et al., 2019). Finally, even though general anxiety is a significant factor in primary school math achievement (Cargnelutti et al., 2017; Pellizzoni et al., 2022) and interacts with WM in affecting children's cognitive performance (Owens et al., 2014), previous studies have never controlled it as a confounding variable.

The current study

Given the sparse and contradictory results of the literature, in the current study we sought to deepen the understanding of the complex interplay between cognitive and emotional factors and math achievement in a sample of late primary school students in the following ways:

1. Evaluating the specific contributions of VSWM and MA on numerical operations and math reasoning tasks retrieved from a standardized math achievement battery after controlling for age and general anxiety
2. Examining the interaction between VSWM and MA by running a simple slopes analysis to explore how math performance is influenced by MA at different levels of VSWM

We considered only the role of the VSWM component because, first, MA seems to display a stronger negative association with VSWM compared with VWM (Moran, 2016; Shackman et al., 2006; Soltanlou et al., 2015; Živković et al., 2022) and has stable effects during the primary school years (Allen & Giofrè, 2021; Liang et al., 2022); second, this component plays an important role in math learning, especially at the end of primary school (e.g., Li & Geary, 2013); and, third, tasks presented in a written format can inherently engage the visual components, influencing strategies that participants choose (Wong & Szücs, 2013).

We hypothesized that both VSWM and MA would affect performance on both numerical operations and math reasoning (Allen et al., 2019; Alloway et al., 2009; Meyer et al., 2010). With respect to the second aim, we predicted that VSWM would moderate the relationship between MA and math performance on the two different tasks. In particular, we aimed to explore how low-, average-, and high-VSWM-capacity individuals' math performance was affected by MA considering math fluency and a math reasoning task. These two math tasks were selected because they required students to solve numerical operations and mathematical reasoning tasks that are well known to be specifically influenced by VSWM (see Allen et al., 2019; Alloway et al., 2009; Meyer et al., 2010).

The novelty of the current research is that we sought to evaluate the complex interplay between MA and WM when administrating different timed math tasks. Previous studies have mainly considered aggregate measures of math achievement, finding that high-WM individuals suffer more from MA (Ramirez et al., 2013, 2016; Vukovic et al., 2013), whereas few studies have considered different math tasks (Sidney et al., 2019; Soltanlou et al., 2019). For instance, considering developmental samples, Soltanlou et al. (2019) found opposite results using a single arithmetic task. Hence, we assessed children with two tasks (i.e., arithmetic and numerical reasoning tasks) to test whether different instruments could lead to variable findings. Another novel aspect of our study is that we used timed tasks given that previous studies in the field have mainly employed tasks without time limits (e.g., Ramirez et al., 2013, 2016; Vukovic et al., 2013). Timed tasks are suitable in this context because they could assess both accuracy and participants' speed. This is of prime importance given that, according to the PET, MA would interfere with WM resources via negative intrusive thoughts, which could lead to poor performance affecting both accuracy and processing speed while solving the task (Eysenck & Calvo, 1992; Eysenck et al., 2007; Núñez-Peña & Suárez-Pellicioni, 2014; Young et al., 2012).

Furthermore, it is important to note that the current study focused on a sample of late primary school children, a developmental period relatively unexplored by previous studies on MA and WM (Soltanlou et al., 2019). Several studies considering early primary school children (Ramirez et al., 2013, 2016; Vukovic et al., 2013) found that high-WM individuals suffer more from MA. On the other hand, Soltanlou et al., (2019) found opposite results when considering children in their last years of primary school. Therefore, it is clear that further research, employing different developmental samples, is necessary.

One last consideration must be made regarding the methods. In the current study, we strengthened our methods both with an adequately powered sample and by controlling for general anxiety, which was typically not controlled in previous studies despite the fact that (a) it is a predictor of math proficiency in primary school (Cargnelutti et al., 2017; Pellizzoni et al., 2022) and (b) several studies have found that low-WM individuals could be more influenced by general anxiety while solving a cognitive task (Owens et al., 2014).

Method

Participants

Participants in the study were 210 students attending the last 3 years of primary school in northern Italy. Participants with a diagnosis or ongoing assessment of a neurodevelopmental disorder or a specific learning disorder, or who had been in Italian school for less than 4 years were not included in the sample. Before starting the study, 8 children were excluded from the sample because they had an ongoing neuropsychiatric diagnosis or assessment, and 6 children were excluded because they were in the Italian school system for less than 4 years. Multiple imputations were used to handle missing data from 5 participants using the predictive mean matching method, replacing missingness by plausible data values and using five imputed datasets to estimate pooled regression parameters (see Van Buuren & Groothuis-Oudshoorn, 2011). A total of 8 participants produced outlier scores on the math tasks and were handled with listwise deletion and removed from the analysis. Thus, the final sample consisted of 202 children (102 male and 100 female) with a mean age of 9.68 years (*SD* = 1.20). All participants were typically developing children who were not diagnosed with any learning or neurodevelopmental disability and did not attend any special needs curriculum. Students were Caucasian, and the socioeconomic status of the sample was primarily middle class and established on the basis of school records. In line with government data on the migration background of Italian pupils (Ministero dell'Istruzione–Ufficio di Statistica [MIUR], 2022), the composition of our sample was 91% composed of citizens born in Italy, 6% of European Union (EU) citizens born outside Italy, and the remainder of non-EU citizens.

After the approval from school principals to take part in the research project, parents gave written consent for their children to participate in the study. Students were informed that their participation was voluntary and that they could withdraw from the study at any time. The study was conducted in accordance with the Declaration of Helsinki and in compliance with the ethical guidelines of the Italian Association of Psychology and the ethical code of the Italian Register of Professional Psychologists. The research was approved by the ethical committee of the University of Trieste.

Measures

Children were tested in two phases. The first assessment session occurred at the beginning of the school year when students' affective (math and general anxiety) and cognitive (VSWM) factors were evaluated. After 5 months from the first session, we evaluated children's math performance employing two different tasks (i.e., math fluency and math reasoning tasks).

Math anxiety

The Abbreviated Math Anxiety Scale (AMAS; Hopko et al., 2003; Italian version adapted by Caviola et al., 2017) is a self-report questionnaire composed of 9 items used to identify children's trait MA level. Participants were asked to indicate, on a 5-point Likert scale (1 = *a little*, 5 = *extremely*), how anxious they would feel in different situations that involve math activities (e.g., "Learn a new topic in math class"). The final score on the AMAS was calculated as the sum of the scores on each item (ranging from 9 to 45), with higher scores corresponding to higher levels of MA.

General anxiety

The Revised Children's Manifest Anxiety Scale (RCMAS-2; Reynolds et al., 2012; Italian edition) is a self-report questionnaire used to measure the level of general anxiety in individuals aged 6 to 19 years. We used the short form composed of 10 items and asked children to judge whether the statements reflected their everyday experience in a binary "yes" (1 point) or "no" (0 points) response format. The total score could range from 0 to 10, with higher scores corresponding to higher levels of general anxiety.

Visuospatial working memory

VSWM was measured employing a computerized version of the Dot Memory task (adaption by Miyake et al., 2001). Participants were asked to remember the sequence and positions of Xs inside a 5 × 5 matrix that later disappeared. After that, they needed to recall and indicate the sequence and positions of these Xs in a new empty matrix. The test was administered adopting a self-terminating procedure, starting with a simple matrix with two randomly positioned Xs. Participants continued as long as they were able to solve at least one of two matrices for a given level, and no feedback was provided. The total score was the sum of correctly recalled positions and sequences and could range from 0 to 70.

Math performance

To assess math performance, we administrated two paper-and-pencil subtests of the AC-MT-3 (Test di Valutazione delle Abilità di Calcolo e del Ragionamento Matematico) 6–14 battery (Cornoldi et al., 2020) that evaluated calculation skills: the math fluency and math reasoning tasks (see Appendix for item examples). The math fluency subtest evaluates students' arithmetic skills and requires solving 15 arithmetic operations (additions and subtractions) as quickly as possible in 1 min. The numbers of addition and subtraction tasks all were composed of two-digit numbers. Furthermore, in 4 additions and 3 subtractions, children were required to perform carrying and borrowing procedures. Children were instructed to complete a series of additions and subtractions as quickly as possible before the test started. Next, children were shown 2 examples (1 addition and 1 subtraction), and then asked to perform a third example on their own. The final score was the number of operations solved correctly, ranging from 0 to 15. The math reasoning subtest assesses children's arithmetical skills and reasoning ability using numerical series. Before beginning this test, children were told that their task was to find, through the identification of a rule, the correct number to fit inside the empty cell in the table. The correct rule was to be inferred from the number sequence in the first row of the table and applied to the row below. Children were then shown two examples of solving the task and asked to solve a third example on their own. Participants had 2 min to solve 12 incomplete numerical matrices with the correct number. Responses were awarded a score of 0 or 1 depending on whether they were incorrect or correct, respectively. The total score could range from 0 to 12.

Results

Descriptive statistics (means and standard deviations), reliability of the measures, and bivariate correlations are shown in Table 1.

Moderation analysis

To assess the specific contributions of VSWM and MA and their interplay on the math fluency and math reasoning task, we performed two multiple regression analyses, one for each considered math task (Fig. 1). MA, VSWM, the interaction term MA × VSWM, and the covariates (general anxiety and age) all were regressed on the two math tasks separately (Table 2). All variables were included as continuous predictors and centered before conducting the regression analyses. The beta effects (β) reported in the tables and the text refer to standardized regression coefficients; that is, for each standard deviation increase in the predictor variable, the beta effects show how many standard

Table 1
Descriptive statistics (means and standard deviations), reliability of the measures according to the literature, and bivariate correlations.

	M	*SD*	Min	Max	*R*	1	2	3	4
1. MA	23.18	7.89	9	44	.90	–			
2. General anxiety	3.81	2.61	0	10	.82	.31**	–		
3. VSWM	17.06	11.29	2	49	.85	−.15*	.06	–	
4. Math fluency task	7.05	2.55	0	10	.77	−.18*	−.08	.20**	–
5. Math reasoning task	4.22	3.39	0	9	.80	−.05	.05	.22**	.08

Note. MA, math anxiety; VSWM, visuospatial working memory.
*p < .05.
**p < .01.

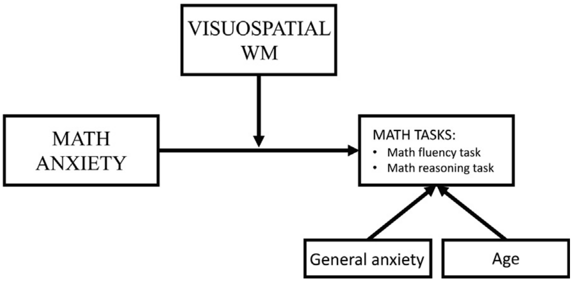


Fig. 1. Path model with the predictor (math anxiety), the moderator (visuospatial WM [working memory]), the dependent variables (math fluency task and math reasoning task), and the covariates (age and general anxiety).

Table 2
Regression analysis considering math fluency task and math reasoning task as dependent variables.

	β	*SE*	*t*	*df*	*p*	95% CI
Math fluency task						
Constant	−.028	.068	−0.421	196	.674	[−.162, .105]
MA	−.154	.072	−2.124	196	.034*	[−.297, −.011]
VSWM	.153	.074	2.058	196	.041*	[.006, .299]
MA × VSWM	−.190	.063	−2.977	196	.003**	[−.316, −.064]
Age	−.133	.072	−1.847	196	.66	[−.274, .009]
General anxiety	−.007	.073	−0.091	196	.927	[−.150, .137]
Math reasoning task						
Constant	−.001	.070	−0.018	196	.985	[−.139, .136]
MA	−.035	.074	−0.475	196	.635	[−.181, .110]
VSWM	.152	.076	1.999	196	.047*	[.002, .302]
MA × VSWM	−.028	.066	−0.429	196	.796	[−.158, .101]
Age	.177	.073	2.403	196	.017*	[.032, .322]
General anxiety	.019	.074	0.259	196	.796	[−.127, .101]

Note. CI, confidence interval. Math anxiety (MA), visuospatial working memory (VSWM), and the interaction between math anxiety and visuospatial working memory (MA × VSWM) were set as predictors. Age and general anxiety were considered as covariates.
*p < .05.
**p < .01.

deviations the dependent variable (i.e., the math fluency or math reasoning task) will change. Cohen's (1988) criteria were used to classify the effect size as small effect (.10 < β < .29), medium effect (.30 < β < .49), or large effect (β > .50).

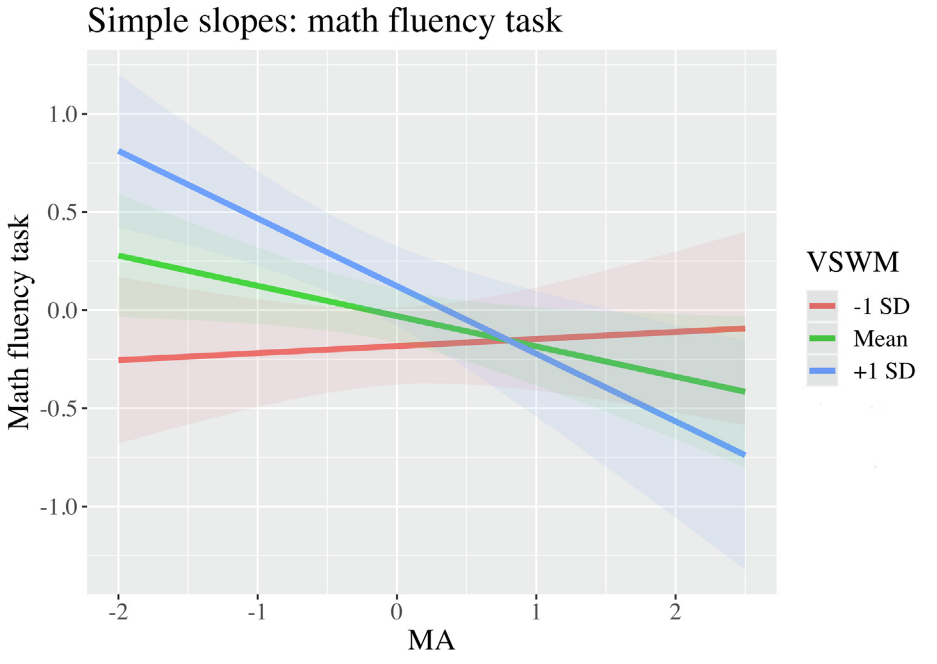


Fig. 2. Simple slope analysis considering visuospatial working memory (VSWM) as a moderator, math anxiety (MA) as a focal predictor, and math fluency scores as the dependent variable. General anxiety and age were set as covariates.

In the first multiple regression model (Table 2), we used a moderation analysis to evaluate the specific contributions of VSWM and MA and their interaction. First, a statistically significant effect of both MA [β = −.154, t(196) = −2.124, p = .034] and VSWM [β = .153, t(196) = 2.058, p = .041] was found on the math fluency task. In particular, MA negatively predicted scores on the task, whereas VSWM positively predicted them. Results also showed a significant main effect of the interaction term MA × VSWM [β = −.19, t(196) = −2.977, p = .003]. Specifically, the simple slope analysis (Fig. 2) revealed that participants with both high VSWM capacity (β = −.345, 95% confidence interval (CI) [−.542, −.011]) and medium VSWM capacity (β = −.154, 95% CI [−.298, −.148]) were significantly and negatively affected by MA in the math fluency task. However, MA did not seem to affect participants with low VSWM capacity (β = .036, 95% CI [−.148, .220]).

In the second multiple regression model (Table 2), we evaluated the specific contributions of MA and VSWM and their interaction on the math reasoning task. Regression analyses found a positive effect of VSWM on the math reasoning task [β = .152, t(196) = 1.999, p = .047], whereas MA did not reach significance [β = −.035, t(196) = −0.475, p = .635]. Moreover, results revealed that the interaction term MA × VSWM was not significant [β = −.028, t(196) = −0.429, p = .796], indicating that VSWM capacity did not moderate the relationship between MA and the math reasoning task. We also examined whether age would interact with MA (MA × Age) and the interaction term MA × VSWM (MA × VSWM × Age) in the matrix reasoning task given that participants' age had a statistically significant influence on that task [β = .177, t(196) = 2.403, p = .017]. Results for both interaction terms (MA × Age and MA × VSWM × Age) showed a marginal statistical effect; therefore, we did not further investigate performing a simple slope analysis.

Discussion

Given the importance of math skills at both the individual and collective levels, it is critical to deepen the understanding of the interplay between MA and VSWM in math learning, as well as to better comprehend which students are most affected by these factors, in order to support the learning process during the development stage (e.g., Ashcraft & Kirk, 2001; Miller & Bichsel, 2004; Owens et al., 2014; Soltanlou et al., 2019). According to the PET (Eysenck & Calvo, 1992), anxiety is assumed to interfere with WM resources, leading to poor performance in math, but it is less clear who are the most affected individuals based on specific task types and age range. In fact, on the one hand, some studies reported that low-WM-capacity individuals would suffer more from the detrimental effects of anxiety due to limited resources, leading to poor performance on cognitive and mathematical tasks (e.g., Ashcraft & Kirk, 2001; Miller & Bichsel, 2004; Owens et al., 2014; Soltanlou et al., 2019). On the other hand, some findings suggested that MA would specifically interfere with advanced memory-based resolution strategies used by high-WM individuals to accomplish math tasks. As a result, individuals with high WM capacity would suffer more from the detrimental effects of MA (Ramirez et al., 2013, 2016; Vukovic et al., 2013).

Given this state of the art, the first aim of the current study was to examine the specific contributions of MA and VSWM in a sample attending the last years of primary school by measuring performance on two separate math tasks, namely the fluency task and math reasoning task. As expected, our data revealed that VSWM was a positive predictor for both tasks. Our results confirm and extend previous research asserting that VSWM is a relevant component in numerical operations and math reasoning (Allen et al., 2019; Alloway et al., 2009; Green et al., 2017; Harari et al., 2013; Meyer et al., 2010), especially in late primary education (e.g., Li & Geary, 2013; Pellizzoni et al., 2022). Partially in accordance with our starting hypothesis, MA negatively predicted students' performance on the math fluency task but not their achievement on the math reasoning task. This finding is in accordance with a previous study of Harari and colleagues (2013), which found that MA did not correlate with a measure similar to the math reasoning task administered in the current study. The inconsistent impact of MA on different math tasks could depend on earlier negative experiences with the specific math tasks we proposed. Indeed, solving arithmetic operations is a commonly evaluated skill in the school context, and children might have perceived the task as threatening based on their previous assessment experiences. In contrast, the math reasoning task is less used in children's math school curricula to assess their math performance and, therefore, may have failed to elicit negative affective reactions. When investigating the role of MA in math performance, future studies should pay closer attention to the tasks.

The second aim of the study was to evaluate the interaction between MA and VSWM, exploring how low-, average-, and high-VSWM-capacity individuals' math performance was affected by MA when considering math fluency and math reasoning tasks. Results on the math fluency task revealed a statistically significant interaction between MA and VSWM, which confirmed our initial hypothesis. In particular, we observed that individuals with high WM capacity were more impaired by MA. Previous studies on children (Ramirez et al., 2013, 2016; Vukovic et al., 2013) and adults (Beilock & Carr, 2005) found a similar pattern of results, where it was hypothesized that MA would interfere with WM-based resolution strategies, resulting in poor performances in children with higher WM capacity (Ramirez et al., 2016). Indeed, solving arithmetic operations necessitates the use of several VSWM-consuming strategies such as the application of specific procedural rules involving the decomposition of the operands in digits, their alignment in columns, the ability to apply carrying–borrowing rules, and the elaboration of partial results (Allen et al., 2020; Caviola et al., 2014; Cragg et al., 2017). Furthermore, the written format could inherently engage the visual components, influencing the strategies chosen by participants (Wong & Szücs, 2013). Our results are in contrast to some studies involving adults (Ashcraft & Kirk, 2001; Miller & Bichsel, 2004) and primary school children (Soltanlou et al., 2019), which found that low-WM individuals suffer more from MA given their fewer resources. Considering developmental samples, Soltanlou et al. (2019) found, contrary to our study, that low-WM individuals were more negatively affected by MA compared with high-WM ones. It must be noted that the authors considered a multiplication learning task that required children to solve one- and two-digit operations. One main difference with our study is that the authors evaluated children's learning rather than task performance; thus, their findings could reflect the fact that high-WM individuals learn more math despite being affected by MA. Studies that found a similar pattern to ours (Ramirez et al., 2013, 2016; Vukovic et al., 2013) mainly evaluated math competence through aggregate scores of math performance that included tasks such as verbal math problems, probability understanding, and geometry. Despite the possibility that aggregate measures could hide how task characteristics influence the interplay between MA and WM, these results highlight that high-WM individuals suffer more from MA on average. On the other hand, in contrast to the starting hypothesis, the relationship between MA and performance was not moderated by different levels of VSWM in the math reasoning task. This could be because MA had no effect on task scores and, thus, had no effect on the performance associated with the different VSWM profiles.

Our results could be interpreted theoretically in the context of strategies that students use when solving mathematical tasks. It is well established in the literature that knowing a variety of math strategies is beneficial for math learning and that using advanced memory-based strategies posits high demands on WM while solving math tasks (Cho et al., 2011; Geary et al., 2004; Laski et al., 2013; Ramirez et al. 2016). As pointed out by Ramirez et al. (2016), suffering from MA would hinder the use of those advanced memory-based strategies, leading high-WM students to display worse math performance. Despite the fact that in our study we did not directly assess math strategies, the pattern of results suggests their likely involvement when considering profile differences in MA, WM, and math performance. Indeed, when considering the math fluency task, high-WM individuals were more affected by MA compared with low-WM individuals. Whether the WM task we considered could influence the results of the current study remains an open question. Indeed, previous studies have used different WM tasks with a wide range of content, including numbers (Ramirez et al., 2013), letters (Ramirez et al., 2016), and visuospatial information (Soltanlou et al., 2019; Vukovic et al., 2013). Furthermore, research using verbal modality (Ramirez et al., 2013, 2016) appears to find greater agreement between findings, whereas research using visuospatial modality appears to have produced mixed findings when considering the interaction between MA and WM (Soltanlou et al., 2019; Vukovic et al., 2013). From this evidence pattern, it seems that the WM modality interacts with MA depending on the children's age. Indeed, studies that focused on verbal tasks have detected interactions with MA in the early grades of primary school (Ramirez et al., 2013, 2016), whereas VSWM seems to have a major role in second grade, third grade (Vukovic et al., 2013), and fifth grade (Soltanlou et al., 2019). In this context, our results may also depend on the central role of VSWM in the last years of primary school when math learning becomes more complex (Ashkenazi et al., 2013; Li & Geary, 2013; Szűcs et al., 2014). Future studies should examine how the interplay between MA and WM modality could vary depending on the considered developmental period.

Taken together, these findings seem to shed some new light on the debate surrounding the interplay between MA and WM in the last years of primary school, a developmental period that has received little attention in the literature. In this context, our results demonstrate that cognitive and emotional factors appear to interact differently depending on the features of the math task. Indeed, children's performance was affected differently by MA depending on VSWM levels. In particular, high-VSWM-capacity students were more negatively affected by MA in a task involving numerical operations but not number reasoning. As a result, tasks' features may explain incongruent findings in the literature, and future studies should take into account different tasks when investigating how MA and WM interplay in math performance. Furthermore, we found that the VSWM component positively affected performance in both the numerical operations and math reasoning tasks, indicating that MA does not entirely drain the protective role of WM resources. This pattern of results suggests that WM, rather than MA, is a better predictor of disciplinary outcomes, and our findings may explain seemingly contradictory evidence in the literature. For instance, a recent study conducted by Soltanlou and colleagues (2019) found that high-WM individuals were less influenced by MA in a multiplication learning intervention. In discussing their results, the authors stated that high-WM individuals would have more resources to deal with math learning and MA. However, it also could be that WM resources represent a stronger predictor of learning outcomes per se compared with MA (Soltanlou et al., 2019). In addition to prior studies, general anxiety was evaluated as a covariate, and it was found that general anxiety does not have a significant influence on math performance. Indeed, past research has shown that the influence of general anxiety is more prevalent in earlier grades of primary school, whereas more specific forms of anxiety (e.g., MA) emerge later (Cargnelutti et al., 2017; Pellizzoni et al., 2022).

Limitations

There are some limitations associated with our study that should be acknowledged and addressed by future research. First, we employed correlational data that could make it difficult to state causal relationships between the examined variables, and for this reason future studies should consider using longitudinal or experimental methods. Furthermore, we evaluated a limited set of variables, and so future research should consider investigating other cognitive factors (Pelegrina et al., 2020) and including an assessment of students' math strategies, as was done in a prior study (Ramirez et al., 2016). Our study also did not test whether the complexity of the task or participants' prior knowledge (Chan et al., 2022; Laski et al., 2014) may have affected the results, aspects that will need to be controlled in future studies. In addition, we did not assess the interaction between different WM modalities and MA in the context of math learning. Indeed, MA appears to interact with the verbal WM modality when it comes to very young children in primary school (Ramirez et al., 2013, 2016), whereas VSWM appears to be more important when older students are considered (Soltanlou et al., 2019; Vukovic et al., 2013). For this reason, future research should take into account the unique contributions of different WM modalities while also exploring their role during development. Given the characteristics of our sample, it is plausible that our results could be more easily generalized to samples of average socioeconomic status and educational background similar to that of Italy. Therefore, the generalizability of our results could be reduced in countries with different methods of organizing mathematics curricula, different language and cultural backgrounds, or educational poverty or an absence of formal scholarization (Pellizzoni et al., 2020).

Conclusions

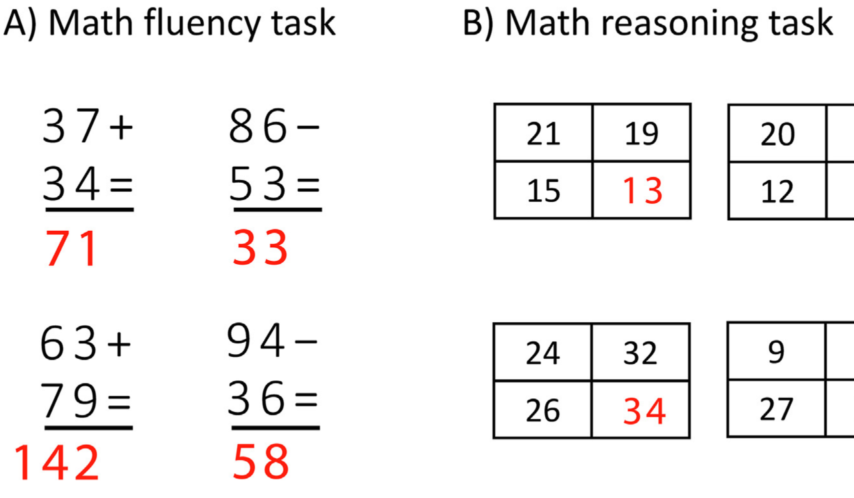
General mathematics assessments often include a broad variety of problem types, requiring children to switch between operations, strategies, and mental models. However, the relationships between different WM components, MA, and mathematics performance are found to vary depending on the type of mathematics tests used. Our findings shed new light on the interplay between MA, VSWM, and math tasks, showing that high-WM individuals would be more affected by MA for specific types of tasks (e.g., math fluency) but not for others (e.g., math reasoning). However, both tasks were positively predicted by VSWM, indicating that its supporting role in math performance is not completely flattened by MA. Our study depicts how a combined interplay of cognitive and emotional factors influences math performance as well as how interindividual differences and task characteristics can explain students' outcomes in learning.

These findings emphasize the importance of considering the effects of anxiety in the context of individuals' cognitive profiles and have important implications in educational settings. We showed that the presence of MA could also hamper the performance of those students who are high in WM capacity, preventing them from reaching their full potential. In this regard, early detection and prevention of negative affective reactions toward math would result in positive outcomes not only in cognitive and mathematical aspects but also in individuals' future academic and occupational success (Passolunghi et al., 2020).

Furthermore, data suggest the need to modulate interventions for specific profiles, considering not only emotional components but also their interaction with cognitive components and specific types of tasks. For this reason, future research should focus on a more targeted intervention, considering different types of children's profiles and learning trajectories, to promote math achievement and empower children and future citizens with appropriate tools to understand the world around them.

Appendix

Math task examples



Note. Some examples of the math fluency (A) and math reasoning (B) task items used in the current study are shown. The solutions for items are shown in red.

References

Allen, K., & Giofrè, D. (2021). A distinction between working memory components as unique predictors of mathematical components in 7–8 year old children. *Educational Psychology, 41*(6), 678–694.
Allen, K., Giofrè, D., Higgins, S., & Adams, J. (2020). Working memory predictors of written mathematics in 7- to 8-year-old children. *Quarterly Journal of Experimental Psychology, 73*(2), 239–248.
Allen, K., Higgins, S., & Adams, J. (2019). The relationship between visuospatial working memory and mathematical performance in school-aged children: A systematic review. *Educational Psychology Review, 31*(3), 509–531.
Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliott, J. (2009). The cognitive and behavioral characteristics of children with low working memory. *Child Development, 80*(2), 606–621.
Ashcraft, M. H., & Kirk, E. P. (2001). The relationships among working memory, math anxiety, and performance. *Journal of Experimental Psychology: General, 130*(2), 224–237.
Ashkenazi, S., & Danan, Y. (2017). The role of mathematical anxiety and working memory on the performance of different types of arithmetic tasks. *Trends in Neuroscience and Education, 7*, 1–10.
Ashkenazi, S., Rosenberg-Lee, M., Metcalfe, A. W., Swigart, A. G., & Menon, V. (2013). Visuo-spatial working memory is an important source of domain-general vulnerability in the development of arithmetic cognition. *Neuropsychologia, 51*(11), 2305–2317.
Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.). *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). Academic Press.
Beilock, S. L., & Carr, T. H. (2005). When high-powered people fail: Working memory and "choking under pressure" in math. *Psychological Science, 16*(2), 101–105.
Beilock, S. L., & DeCaro, M. S. (2007). From poor performance to success under stress: Working memory, strategy selection, and mathematical problem solving under pressure. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(6), 983–998.
Beilock, S. L., Kulp, C. A., Holt, L. E., & Carr, T. H. (2004). More on the fragility of performance: Choking under pressure in mathematical problem solving. *Journal of Experimental Psychology: General, 133*(4), 584–600.
Berg, D. H. (2008). Working memory and arithmetic calculation in children: The contributory roles of processing speed, short-term memory, and reading. *Journal of Experimental Child Psychology, 99*(4), 288–308.
Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology, 33*(3), 205–228.
Bynner, J. M. (1997). Basic skills in adolescents' occupational preparation. *Career Development Quarterly, 45*(4), 305–321.
Carey, E., Hill, F., Devine, A., & Szűcs, D. (2016). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Frontiers in Psychology, 6*, Article 1987.

Cargnelutti, E., Tomasetto, C., & Passolunghi, M. C. (2017). The interplay between affective and cognitive factors in shaping early proficiency in mathematics. *Trends in Neuroscience and Education, 8*, 28–36.
Caviola, S., Mammarella, I. C., Lucangeli, D., & Cornoldi, C. (2014). Working memory and domain-specific precursors predicting success in learning written subtraction problems. *Learning and Individual Differences, 36*, 92–100.
Caviola, S., Primi, C., Chiesi, F., & Mammarella, I. C. (2017). Psychometric properties of the Abbreviated Math Anxiety Scale (AMAS) in Italian primary school children. *Learning and Individual Differences, 55*, 174–182.
Caviola, S., Toffalini, E., Giofrè, D., Ruiz, J. M., Szűcs, D., & Mammarella, I. C. (2022). Math performance and academic anxiety forms, from sociodemographic to cognitive aspects: A meta-analysis on 906,311 participants. *Educational Psychology Review, 34*, 363–399.
Chan, J.-Y.-C., Ottmar, E. R., & Lee, J.-E. (2022). Slow down to speed up: Longer pause time before solving problems relates to higher strategy efficiency. *Learning and Individual Differences, 93*. Article 102109.
Cho, S., Ryali, S., Geary, D. C., & Menon, V. (2011). How does a child solve 7 + 8? Decoding brain activity patterns associated with counting and retrieval strategies. *Developmental Science, 14*(5), 989–1001.
Cipora, K., Santos, F. H., Kucian, K., & Dowker, A. (2022). Mathematics anxiety—Where are we and where shall we go? *Annals of the New York Academy of Sciences, 1513*, 10–20.
Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Routledge.
Cohen, L. D., & Rubinsten, O. (2021). The complex pathways toward the development of math anxiety and links with achievements. In W. Fias & A. Henik (Eds.), *Heterogeneous contributions to numerical cognition* (pp. 311–326). Academic Press.
Cornoldi, C., Mammarella, I. C., & Caviola, S. (2020). *AC-MT-3: Test di Valutazione delle Abilità di Calcolo e del Ragionamento Matematico.* Edizioni Erickson.
Cragg, L., Richardson, S., Hubber, P. J., Keeble, S., & Gilmore, C. (2017). When is working memory important for arithmetic? The impact of strategy and age. *PLoS One, 12*(12). Article e188693.
De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology, 103*(2), 186–201.
DeCaro, M. S., Rotar, K. E., Kendra, M. S., & Beilock, S. L. (2010). Diagnosing and alleviating the impact of performance pressure on mathematical problem solving. *Quarterly Journal of Experimental Psychology, 63*(8), 1619–1630.
Devine, A., Hill, F., Carey, E., & Szűcs, D. (2018). Cognitive and emotional math problems largely dissociate: Prevalence of developmental dyscalculia and mathematics anxiety. *Journal of Educational Psychology, 110*(3), 431–444.
Donolato, E., Toffalini, E., Giofrè, D., Caviola, S., & Mammarella, I. C. (2020). Going beyond mathematics anxiety in primary and middle school students: The role of ego-resiliency in mathematics. *Mind, Brain, and Education, 14*(3), 255–266.
Dougherty, C. (2003). Numeracy, literacy and earnings: Evidence from the National Longitudinal Survey of Youth. *Economics of Education Review, 22*(5), 511–521.
Dowker, A., Sarkar, A., & Looi, C. Y. (2016). Mathematics anxiety: What have we learned in 60 years? *Frontiers in Psychology, 7*. Article 508.
Eysenck, M. W., & Calvo, M. G. (1992). Anxiety and performance: The processing efficiency theory. *Cognition & Emotion, 6*(6), 409–434.
Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*(2), 336–363.
Foley, A. E., Herts, J. B., Borgonovi, F., Guerriero, S., Levine, S. C., & Beilock, S. L. (2017). The math anxiety–performance link: A global phenomenon. *Current Directions in Psychological Science, 26*(1), 52–58.
Fonteyne, L., Duyck, W., & De Fruyt, F. (2017). Program-specific prediction of academic achievement on the basis of cognitive and non-cognitive factors. *Learning and Individual Differences, 56*, 34–48.
Friso-van den Bos, I., Van der Ven, S. H., Kroesbergen, E. H., & Van Luit, J. E. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review, 10*, 29–44.
Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., Seethaler, P. M., Bryant, J. D., & Schatschneider, C. (2010). Do different types of school mathematics development depend on different constellations of numerical versus general cognitive abilities? *Developmental Psychology, 46*(6), 1731–1746.
Furlong, M., McLoughlin, F., McGilloway, S., & Geary, D. (2016). Interventions to improve mathematical performance for children with mathematical learning difficulties (MLD). *Cochrane Database of Systematic Reviews, 2016*(4), Article CD012130.
Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*(2), 177–190.
Geary, D. C., Hoard, M. K., Byrd-Craven, J., & DeSoto, M. C. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology, 88*(2), 121–151.
Geary, D. C., Hoard, M. K., Byrd-Craven, J., Nugent, L., & Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Development, 78*(4), 1343–1359.
Gerardi, K., Goette, L., & Meier, S. (2013). Numerical ability predicts mortgage default. *Proceedings of the National Academy of Sciences of the United States of America, 110*(28), 11267–11271.
Giofrè, D., Borella, E., & Mammarella, I. C. (2017). The relationship between intelligence, working memory, academic self-esteem, and academic achievement. *Journal of Cognitive Psychology, 29*(6), 731–747.
Giofrè, D., Donolato, E., & Mammarella, I. C. (2018). The differential role of verbal and visuospatial working memory in mathematics and reading. *Trends in Neuroscience and Education, 12*, 1–6.
Giofrè, D., Mammarella, I. C., & Cornoldi, C. (2014). The relationship among geometry, working memory, and intelligence in children. *Journal of Experimental Child Psychology, 123*, 112–128.
Giofrè, D., Mammarella, I. C., Ronconi, L., & Cornoldi, C. (2013). Visuospatial working memory in intuitive geometry, and in academic achievement in geometry. *Learning and Individual Differences, 23*, 114–122.
Green, C. T., Bunge, S. A., Chiongbian, V. B., Barrow, M., & Ferrer, E. (2017). Fluid reasoning predicts future mathematical performance among children and adolescents. *Journal of Experimental Child Psychology, 157*, 125–143.

Gross, J., Hudson, C., & Price, D. (2009). *The long term costs of numeracy difficulties*. Every Child a Chance Trust.
Harari, R. R., Vukovic, R. K., & Bailey, S. P. (2013). Mathematics anxiety in young children: An exploratory study. *Journal of Experimental Education, 81*(4), 538–555.
Higbee, J. L., & Thomas, P. V. (1999). Affective and cognitive factors related to mathematics achievement. *Journal of Developmental Education, 23*(1), 8–32.
Hitch, G. J., & McAuley, E. (1991). Working memory in children with specific arithmetical learning difficulties. *British Journal of Psychology, 82*(3), 375–386.
Hopko, D. R., Mahadevan, R., Bare, R. L., & Hunt, M. K. (2003). The Abbreviated Math Anxiety Scale (AMAS): Construction, validity, and reliability. *Assessment, 10*(2), 178–182.
Justicia-Galiano, M. J., Martín-Puga, M. E., Linares, R., & Pelegrina, S. (2017). Math anxiety and math performance in children: The mediating roles of working memory and math self-concept. *British Journal of Educational Psychology, 87*(4), 573–589.
Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*(2), 189–217.
Laski, E. V., Casey, B. M., Yu, Q., Dulaney, A., Heyman, M., & Dearing, E. (2013). Spatial skills as a predictor of first grade girls' use of higher level arithmetic strategies. *Learning and Individual Differences, 23*, 123–130.
Laski, E. V., Ermakova, A., & Vasilyeva, M. (2014). Early use of decomposition for addition and its relation to base-10 knowledge. *Journal of Applied Developmental Psychology, 35*(5), 444–454.
Lee, K., Ning, F., & Goh, H. C. (2014). Interaction between cognitive and non-cognitive factors: The influences of academic goal orientation and working memory on mathematical performance. *Educational Psychology, 34*(1), 73–91.
Li, Y., & Geary, D. C. (2013). Developmental gains in visuospatial memory predict gains in mathematics achievement. *PLoS One, 8*(7). Article e70160.
Liang, Z., Dong, P., Zhou, Y., Feng, S., & Zhang, Q. (2022). Whether verbal and visuospatial working memory play different roles in pupil's mathematical abilities. *British Journal of Educational Psychology, 92*(2). Article 12454.
Lu, L., Weber, H. S., Spinath, F. M., & Shi, J. (2011). Predicting school achievement from cognitive and non-cognitive variables in a Chinese sample of elementary school children. *Intelligence, 39*, 130–140.
Maehler, C., & Schuchardt, K. (2016). The importance of working memory for school achievement in primary school children with intellectual or learning disabilities. *Research in Developmental Disabilities, 58*, 1–8.
Mammarella, I. C., Caviola, S., Cornoldi, C., & Lucangeli, D. (2013). Mental additions and verbal-domain interference in children with developmental dyscalculia. *Research in Developmental Disabilities, 34*(9), 2845–2855.
Mattarella-Micke, A., Mateo, J., Kozak, M. N., Foster, K., & Beilock, S. L. (2011). Choke or thrive? The relation between salivary cortisol and math performance depends on individual differences in working memory and math-anxiety. *Emotion, 11*(4), 1000–1005.
Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences, 20*(2), 101–109.
Miller, H., & Bichsel, J. (2004). Anxiety, working memory, gender, and math performance. *Personality and Individual Differences, 37*(3), 591–606.
Ministero dell'Istruzione–Ufficio di Statistica. (2022). *Gli alunni con cittadinanza non italiana.* MIUR.
Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent variable analysis. *Journal of Experimental Psychology: General, 130*, 621–640.
Moran, T. P. (2016). Anxiety and working memory capacity: A meta-analysis and narrative review. *Psychological Bulletin, 142*(8), 831–864.
Namkung, J. M., Peng, P., & Lin, X. (2019). The relation between mathematics anxiety and mathematics performance among school-aged students: A meta-analysis. *Review of Educational Research, 89*(3), 459–496.
Núñez-Peña, M. I., & Suárez-Pellicioni, M. (2014). Less precise representation of numerical magnitude in high math-anxious individuals: An ERP study of the size and distance effects. *Biological Psychology, 103*, 176–183.
Organization for Economic Cooperation and Development. (2013). *PISA 2012 assessment and analytical framework: Mathematics, reading, science, problem solving and financial literacy.* OECD.
Owens, M., Stevenson, J., Hadwin, J. A., & Norgate, R. (2012). Anxiety and depression in academic performance: An exploration of the mediating factors of worry and working memory. *School Psychology International, 33*(4), 433–449.
Owens, M., Stevenson, J., Hadwin, J. A., & Norgate, R. (2014). When does anxiety help or hinder cognitive test performance? The role of working memory capacity. *British Journal of Psychology, 105*(1), 92–101.
Owens, M., Stevenson, J., Norgate, R., & Hadwin, J. A. (2008). Processing efficiency theory in children: Working memory as a mediator between trait anxiety and academic performance. *Anxiety, Stress, & Coping, 21*(4), 417–430.
Passolunghi, M. C., Cargnelutti, E., & Pastore, M. (2014). The contribution of general cognitive abilities and approximate number system to early mathematics. *British Journal of Educational Psychology, 84*(4), 631–649.
Passolunghi, M. C., Cargnelutti, E., & Pellizzoni, S. (2019). The relation between cognitive and emotional factors and arithmetic problem-solving. *Educational Studies in Mathematics, 100*(3), 271–290.
Passolunghi, M. C., De Vita, C., & Pellizzoni, S. (2020). Math anxiety and math achievement: The effects of emotional and math strategy training. *Developmental Science, 23*(6). Article 12964.
Passolunghi, M. C., & Mammarella, I. C. (2010). Spatial and visual working memory ability in children with difficulties in arithmetic word problem solving. *European Journal of Cognitive Psychology, 22*(6), 944–963.
Passolunghi, M. C., & Pazzaglia, F. (2005). A comparison of updating processes in children good or poor in arithmetic word problem-solving. *Learning and Individual Differences, 15*(4), 257–269.
Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Journal of Experimental Child Psychology, 88*(4), 348–367.
Pelegrina, S., Justicia-Galiano, M. J., Martín-Puga, M. E., & Linares, R. (2020). Math anxiety and working memory updating: Difficulties in retrieving numerical information from working memory. *Frontiers in Psychology, 11*. Article 669.

Pellizzoni, S., Apuzzo, G. M., De Vita, C., Agostini, T., Ambrosini, M., & Passolunghi, M. C. (2020). Exploring EFs and math abilities in highly deprived contexts. *Frontiers in Psychology, 11*. Article 383.
Pellizzoni, S., Cargnelutti, E., Cuder, A., & Passolunghi, M. C. (2022). The interplay between math anxiety and working memory on math performance: A longitudinal study. *Annals of the New York Academy of Sciences, 1510*(1), 132–144.
Peterson, P. E., Woessmann, L., Hanushek, E. A. & Lastra-Anadón, C. X. (2011). *Globally challenged: Are U.S. students ready to compete? The latest on each state's international standing in math and reading* (PEPG Report No. 11-03). Program on Education Policy and Governance.
Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences, 20*(2), 110–122.
Ramirez, G., Chang, H., Maloney, E. A., Levine, S. C., & Beilock, S. L. (2016). On the relationship between math anxiety and math achievement in early elementary school: The role of problem solving strategies. *Journal of experimental child psychology, 141*, 83–100.
Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2013). Math anxiety, working memory, and math achievement in early elementary school. *Journal of Cognition and Development, 14*(2), 187–202.
Reynolds, C. R., Richmond, B. O., Sella, F., Scozzari, S., & Di Pietro, M. (2012). *Revised Children's Manifest Anxiety Scale 2nd edition: Manuale.* Giunti OS Organizzazioni Speciali.
Richardson, F. C., & Suinn, R. M. (1972). The Mathematics Anxiety Rating Scale: Psychometric data. *Journal of Counseling Psychology, 19*(6), 551–554.
Rivera-Batiz, F. L. (1992). Quantitative literacy and the likelihood of employment among young adults in the United States. *Journal of Human Resources, 27*, 313–328.
Rubinsten, O., Marciano, H., Eidlin Levy, H., & Daches Cohen, L. (2018). A framework for studying the heterogeneity of risk factors in math anxiety. *Frontiers in Behavioral Neuroscience, 12*. Article 291.
Shackman, A. J., Sarinopoulos, I., Maxwell, J. S., Pizzagalli, D. A., Lavric, A., & Davidson, R. J. (2006). Anxiety selectively disrupts visuospatial working memory. *Emotion, 6*(1), 40–61.
Sidney, P. G., Thalluri, R., Buerke, M. L., & Thompson, C. A. (2019). Who uses more strategies? Linking mathematics anxiety to adults' strategy variability and performance on fraction magnitude tasks. *Thinking & Reasoning, 25*(1), 94–131.
Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development, 60*(4), 973–980.
Soltanlou, M., Artemenko, C., Dresler, T., Fallgatter, A. J., Ehlis, A. C., & Nuerk, H. C. (2019). Math anxiety in combination with low visuospatial memory impairs math learning in children. *Frontiers in Psychology, 10*. Article 89.
Soltanlou, M., Pixner, S., & Nuerk, H. C. (2015). Contribution of working memory in multiplication fact network in children may shift from verbal to visuo-spatial: A longitudinal investigation. *Frontiers in Psychology, 6,* Article 1062.
Sorvo, R., Kiuru, N., Koponen, T., Aro, T., Viholainen, H., Ahonen, T., & Aro, M. (2022). Longitudinal and situational associations between math anxiety and performance among early adolescents. *Annals of the New York Academy of Sciences, 1514*, 174–186.
Swanson, H. L. (2008). Working memory and intelligence in children: What develops? *Journal of Educational Psychology, 100*(3), 581–602.
Szűcs, D., Devine, A., Soltesz, F., Nobes, A., & Gabriel, F. (2014). Cognitive components of a mathematical processing network in 9-year-old children. *Developmental Science, 17*(4), 506–524.
Thompson, P. W. (1996). Imagery and the development of mathematical reasoning. In L. P. Steffe, B. Greer, P. Nesher, P. Cobb, & G. Goldin (Eds.), *Theories of learning mathematics* (pp. 267–283). Lawrence Erlbaum.
Tomasetto, C., Morsanyi, K., Guardabassi, V., & O'Connor, P. A. (2021). Math anxiety interferes with learning novel mathematics contents in early elementary school. *Journal of Educational Psychology, 113*, 315–329.
Van Ameringen, M., Mancini, C., & Farvolden, P. (2003). The impact of anxiety disorders on educational achievement. *Journal of Anxiety Disorders, 17*(5), 561–571.
Van Buuren, S., & Groothuis-Oudshoorn, K. (2011). MICE: Multivariate imputation by chained equations in R. *Journal of Statistical Software, 45*, 1–67.
Vukovic, R. K., Kieffer, M. J., Bailey, S. P., & Harari, R. R. (2013). Mathematics anxiety in young children: Concurrent and longitudinal associations with mathematical performance. *Contemporary Educational Psychology, 38*(1), 1–10.
Wechsler, D. (2017). *Wechsler Individual Achievement Test—Third UK Edition (WIAT-III UK).* Pearson Assessment.
Wong, B., & Szücs, D. (2013). Single-digit Arabic numbers do not automatically activate magnitude representations in adults or in children: Evidence from the symbolic same–different task. *Acta Psychologica, 144*(3), 488–498.
Woodward, L. J., & Fergusson, D. M. (2001). Life course outcomes of young people with anxiety disorders in adolescence. *Journal of the American Academy of Child & Adolescent Psychiatry, 40*(9), 1086–1093.
Wu, S. S., Barth, M., Amin, H., Malcarne, V., & Menon, V. (2012). Math anxiety in second and third graders and its relation to mathematics achievement. *Frontiers in Psychology, 3*. Article 162.
Wu, S. S., Chen, L., Battista, C., Smith Watts, A. K., Willcutt, E. G., & Menon, V. (2017). Distinct influences of affective and cognitive factors on children's non-verbal and verbal mathematical abilities. *Cognition, 166*, 118–129.
Young, C. B., Wu, S. S., & Menon, V. (2012). The neurodevelopmental basis of math anxiety. *Psychological Science, 23*(5), 492–501.
Zhang, J., Zhao, N., & Kong, Q. P. (2019). The relationship between math anxiety and math performance: A meta-analytic investigation. *Frontiers in Psychology, 10,* Article 1613.
Živković, M., Pellizzoni, S., Mammarella, I. C., & Passolunghi, M. C. (2022). The relationship between math anxiety and arithmetic reasoning: The mediating role of working memory and self-competence. *Current Psychology*. https://doi.org/10.1007/s12144-022-02765-0. Advance online publication.