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Math anxiety and math achievement in primary school children: Longitudinal relationship and predictors

Monika Szczygieł[a,*], Denes Szűcs[b], Enrico Toffalini[c]

[a] Institute of Psychology, Jagiellonian University in Kraków, ul. Ingardena 6, 30-060, Kraków, Poland
[b] Department of Psychology, University of Cambridge, Downing Street, Cambridge, CB2 3EB, UK
[c] Department of General Psychology, Univeristy of Padova, Via Venezia, 8, 35131, Padova, Italy

A R T I C L E I N F O

Keywords:
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A B S T R A C T

Background: Math anxiety (MA) and math achievement (MATH) are related, but the direction of their relationship and their predictors are still unclear.
Aims: We tested whether MATH predicts MA (Deficit Theory), MA predicts MATH (Debilitating Anxiety Theory), or whether MA and MATH have reciprocal relationships (Reciprocal Theory). Further, we established whether MA at T0, T1, and T2 and MATH at T1 and T2 were predicted by gender, general anxiety, fluid intelligence, verbal and visuospatial working memory, and symbolic and non-symbolic numerical representations tested at T0.
Sample: We tested 337 Polish primary school children.
Methods: We analyzed longitudinal data at three time points: T0 – the beginning of the first grade, T1 – the end of the first grade, T2 – the end of the second grade.
Results: MATH at T1 predicted MA at T2 and MA at T1 predicted MATH at T2 (supporting the Reciprocal Theory). Additionally, MATH at T1 was predicted by fluid intelligence, visuospatial working memory, and symbolic numerical representation; MATH at T2 by fluid intelligence, verbal working memory, and MATH at T1. MA at T0 was predicted by general anxiety and symbolic numerical representation, MA at T1 by MA at T0 and gender, and MA at T2 by MA at T1.
Conclusions: The results support the Reciprocal Theory of the MA and MATH relationship. MA is predicted by general anxiety, knowledge of mathematical symbols and gender. MATH is predicted by fluid intelligence, working memory and knowledge of mathematical symbols.

1. Introduction

1.1. The relationship between math anxiety and math achievement

Strong mathematical skills are desirable in contemporary societies (OECD, 2018a). STEM (Science, Technology, Engineering, Mathematics) graduates often earn more than others, and countries with many STEM specialists are rapidly developing (Sun et al., 2020). However, STEM education depends on the foundations acquired during the earliest years of education (Kennedy & Tunnicliffe, 2022). Children with math difficulties at the start of school tend to develop substantially worse math skills than children with strong early math skills (Du et al., 2021; Geary, 2011; Mononen et al., 2022; Quintero & Wang, 2023; Song et al., 2021). Therefore, it is important to understand the factors affecting the development of math skills in primary school children.

Here, we focus on math anxiety (MA), a construct that has a reliable negative relationship with math achievement (Barroso et al., 2021; Namkung, Peng, & Lin, 2019; Zhang et al., 2019). 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" (Richardson & Suinn, 1972, p. 551). The negative relationship between MA and math achievement already appears during early schooling (Barroso et al., 2021; Zhang et al., 2019). However, the direction of the relationship between MA and math achievement is debated (Carey et al., 2016; Chang and Beilock, 2016). The Deficit Theory assumes that failures in math lead to higher MA. In contrast, the Debilitating Anxiety Theory assumes that MA leads to avoidance of math learning and in turn difficulties in mathematics. The Reciprocal Theory suggests that previous math achievement affects students' MA that in turn affects future mathematical performance. Determining the

* Corresponding author.
E-mail addresses: monika.szczygiel@uj.edu.pl (M. Szczygieł), ds377@cam.ac.uk (D. Szűcs), enrico.toffalini@unipd.it (E. Toffalini).

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direction of the relationship between MA and achievement is of great practical importance as better understanding can lead to educational recommendations that can support mathematics teaching. Below we discuss the above-mentioned theories of the MA and math achievement relationship (for a detailed review, see Carey et al., 2016).

Deficit Theory. According to Deficit Theory, low math performance leads to high MA (Carey et al., 2016). For example, in a U.S. sample of middle and high school students Ma and Xu (2004) found that MA was predicted by math achievement but not vice versa. Wang et al. (2020) showed in Italian high school students that math achievement predicted MA longitudinally but not vice versa. Such results may be explained by cumulative math problems and avoidance of mathematics during the course of education. Some results also support the validity of the Deficit Theory in younger children. Data from Italian fourth-graders and Canadian 7–13 year-olds, indicated that those with math learning disabilities had greater MA than children without such problems (Passolunghi, 2011; Rubinsten & Tannock, 2010). Both studies suggested that level of math achievement determines level of MA. A longitudinal study conducted by Sorvo et al. (2019) with Finnish primary school-aged children also supported Deficit Theory by demonstrating that prior low arithmetic achievement predicted later high anxiety about failure in mathematics.

Debilitating Anxiety Theory. Most MA research in children tested the hypothesis that MA has a detrimental effect on math achievement. Results from a U.S. sample of third-grade children indicated that MA in second grade predicted children's math achievement in third grade only for children with higher levels of working memory (Vukovic et al., 2013). In contrast, a follow-up study of Chinese children from second to third grade indicated that MA longitudinally predicted math achievement regardless of working memory resources (Ching, 2017). Pantoja et al. (2020) found that U.S. children's first-grade MA score predicted their math achievement in third grade. These studies did not test the effect of math achievement on MA, so it is not known whether math achievement predicted MA scores in these samples. One study tested the bidirectional relationship and supported the Debilitating Anxiety Theory. Cargnelutti et al. (2017) showed that MA in second grade predicted math achievement in Italian third graders, while math achievement in second grade did not predict MA in third grade. Some indirect findings also support the Debilitating Anxiety Theory. For example, it has been observed that MA affects math achievement via disturbing working memory resources in young children (Krinzinger et al., 2009) and in adults (Skagerlund et al., 2019).

Reciprocal Theory Evidence collected for the Deficit Theory and the Debilitating Anxiety Theory suggests that MA and math achievement may be related in a vicious cycle (Carey et al., 2016). This hypothesis is likely, especially because previous studies often did not test the longitudinal bidirectional relationship. One of the studies that supported the Reciprocal Theory is that of Pekrun et al. (2017) who tested German fifth to ninth graders. Their results indicated that positive emotions predicted higher math achievement and achievement predicted greater positive emotions. Moreover, negative emotions predicted lower math achievement and achievement led to more negative math emotions in a vicious cycle. Similar results that confirmed a bidirectional relationship between MA and math achievement were presented in a study conducted among Chinese fourth to sixth graders (Du et al., 2021) and German students from fifth to seventh grades (Aldrup et al., 2020). Some studies with younger children also support the Reciprocal Theory. A recent study conducted with U.S. first and second graders found that MA and math achievement mutually predicted each other through a six month period (Gunderson et al., 2018). However, the prediction of MA from math achievement was stronger than the opposite causal path.

The above review demonstrates that all three above mentioned theories are supported by some robust studies. However, although previous studies showed that both math achievement and MA are predicted by multiple factors (i.e. gender, general anxiety, fluid intelligence, verbal and visuospatial working memory, symbolic and non-symbolic numerical representations), most studies that tested the MA-math achievement link did not sufficiently consider variables that could predict them. The present study aims to fill this gap and tests the relationship between MA and math achievement, taking into account their likely predictors. By considering likely predictors of MA and math achievement in models testing the longitudinal relationship between MA and math achievement we can gain a nuanced understanding of the potentially complex multi-variable relationships shaping MA and math achievement. Below we consider potential predictor variables.

1.2. Predictors of math achievement

Beyond MA, intelligence (Chu et al., 2016; Primi et al., 2010), verbal and visuospatial working memory (Bull et al., 2008; Soltanlou et al., 2019), symbolic and non-symbolic numerical representations (Cueli et al., 2019; Gilmore et al., 2013; Hornung et al., 2014), and gender (Breda and Napp, 2019; Van Mier et al., 2019) are often studied as potential predictors of math achievement. Intelligence refers to the overall cognitive capacity of individuals, including the ability to reason, solve problems, learn, and adapt to new situations. More intelligent children learn mathematics faster and more effectively than less intelligent ones and achieve better mathematical results (Chu et al., 2016). Math problem solving requires the manipulation and organization of multiple pieces of information simultaneously, e.g., when solving complex equations, and working memory helps to keep track of numbers, operations, and intermediate results. Therefore, children with better working memory resources process and manipulate mathematical information more accurately and faster, and achieve higher scores in mathematical tests than those with weaker working memory resources (Soltanlou et al., 2019). It has also been argued that strong non-symbolic and symbolic numerical representations may provide solid foundations for mathematical understanding and proficiency (Hornung et al., 2014). They may enable individuals to make sense of mathematical concepts, perform calculations, solve problems, and communicate mathematically. Gender differences are often considered in mathematics (Breda and Napp, 2019; OECD, 2019) and their presence or absence may depend on multiple factors. These factors include cultural influences, educational systems, the presence of mathematical stereotype threat, the nature of the mathematical tasks, parental expectations and support, and grade level (Breda and Napp, 2019; OECD, 2019). Therefore, it is useful to consider gender as a potential predictor of math achievement. While MA has received more attention in research, general anxiety as a predictor of math achievement has been relatively underexplored (Carey, Devine, Hill, & Szűcs, 2017; Hill et al., 2016). However, a recent meta-analysis by Caviola et al. (2022) revealed that general anxiety has a moderate negative relationship with math achievement. This association can be attributed to the impact of general anxiety on cognitive functioning (mainly attention and working memory) and overall performance in mathematical tasks. Additionally, it can be inferred that the connection between general anxiety and math performance arises from the influence of general anxiety on MA, and MA, in turn, is associated with math achievement (Carey, Devine, et al., 2017).

Although previous robust research has examined the predictors of early childhood math achievement (e.g., Gunderson et al., 2018; Memisevic et al., 2018; Ramirez et al., 2016; Sasanguie et al., 2012), most studies had cross-sectional design and/or did not simultaneously include sociodemographic (e.g., gender), domain-general cognitive (e.g., fluid intelligence and verbal and visuospatial working memory), domain-specific cognitive (e.g., symbolic and non-symbolic numerical representations), and emotional (e.g., general anxiety and math anxiety) variables as predictors in one model. For example, it was observed that symbolic and non-symbolic numerical representations are more important in predicting math achievement when domain-general cognitive abilities are not examined than when those abilities are controlled for (Caviola et al., 2020; Gross et al., 2018; Nelwan et al., 2022; Purpura & Simms, 2018). However, in the above studies emotional factors were not controlled for. Other studies showed that math anxiety and numerical abilities (mental number line) independently predict math performance in children (Pantoja et al., 2020). However, this study did not consider general anxiety, gender, and general-domain cognitive variables so likely the pattern of the results would change if such variables were considered.

In light of the above, we aim to test whether sociodemographic, domain-general and domain-specific cognitive variables and emotional variables measured at the beginning of the first grade determine the level of math achievement at the end of the first grade and whether they continue to predict math achievement at the end of the second grade beyond the level of math achievement in the first grade. We are also interested in which of these variables are the strongest predictors of math achievement.

1.3. Predictors of MA

While there is evidence for a reciprocal relationship between MA and math achievement, there is a notable disparity in the amount of systematic research conducted on predictors of MA (Meece et al., 1990) compared to predictors of math achievement. Previous studies indicate that MA may be associated with variables that are also related to math achievement, including gender (Caviola et al., 2022), general anxiety (Wang et al., 2014), intelligence (Hembree, 1990; Schillinger et al., 2018), working memory (Finell et al., 2022; Justicia-Galiano et al., 2017), and numerical representations (Braham and Libertus, 2018; Lindskog et al., 2017; Maldonado Moscoso et al., 2020, 2022; Maloney et al., 2010, 2011; Núñez-Peña & Suárez-Pellicioni, 2014; Skagerlund et al., 2019). However, the results of previous studies on MA predictors are inconsistent.

Research on the gender gap in MA among primary and secondary students has yielded mixed findings. For example, Harari et al. (2013), Ramirez et al. (2013), and Van Mier et al. (2019) found no significant gender difference in MA while Carey, Devine, et al. (2017), Devine et al. (2012), and Hill et al. (2016), have reported higher levels of MA among girls compared to boys. Substantial gender gap in MA has also been reported by the 2012 international PISA study in 15-year-olds in most countries (OECD, 2013). General anxiety may play a role in the gender differences observed in MA, potentially acting as a mediator between gender and MA (Carey, Devine et al., 2017; Szczygieł, 2020). This implies that higher levels of general anxiety experienced by individuals could contribute to the gender disparities in MA. Previous research consistently indicated a positive association between MA and general anxiety, with greater MA being associated with higher levels of general anxiety (Hill et al., 2016; Szczygieł, 2020; Wang et al., 2014). Individuals who exhibit excessive and persistent worry and anxiety across various aspects of life may also experience heightened worry and anxiety in math-specific situations.

Previous research suggests a weak relationship between intelligence and MA (Hembree, 1990; Schillinger et al., 2018), however, it appears that numerical intelligence, rather than verbal intelligence, plays a more significant role in predicting the level of MA (Schillinger et al., 2018). It is likely that more intelligent students, especially in numerical area, cope better with mathematical tasks and therefore experience lower level of MA. However, the relationship between intelligence and MA in early school age children is not yet well understood. More is known about the relationship between working memory and MA. Previous studies have shown that verbal or visuospatial working memory is negatively related to MA in children (Justicia-Galiano et al., 2017; Pellizzoni et al., 2022; Živković et al., 2023). It is thought that MA leads to intrusive thoughts and overwhelming cognitive load, and increases an individual's attention to threat-related factors (Dowker et al., 2016; Finell et al., 2022). Consequently, worrisome thoughts may deprive children of working memory resources leading to a decline in mathematical performance (Finell et al., 2022; Justicia-Galiano et al., 2017; Ng & Lee, 2019). Finally, Maloney et al. (2010, 2011) proposed the hypothesis that MA is related to deficits in the symbolic numerical magnitude representation. The development of math anxiety may be a result of a basic low-level deficit in numerical processing which in turn compromises the development of advanced mathematical skills. Other research also suggests that symbolic and non-symbolic numerical representations may be related to MA (Braham and Libertus, 2018; Lindskog et al., 2017; Maldonado Moscoso et al., 2020, 2022; Maloney et al., 2010, 2011; Núñez-Peña & Suárez-Pellicioni, 2014; Skagerlund et al., 2019). However, many studies could not find such a relationship (Braham and Libertus, 2018; Colome, 2019; Dietrich et al., 2015; Maldonado Moscoso et al., 2020, 2022; Silver et al., 2022). It should be noted, that the studies on the relationship between MA and symbolic/non-symbolic numerical representations were conducted among adults, and further studies are needed in groups of children.

Although much is known about the correlates of MA, there has been no systematic research to date to clarify which variables are the most responsible for MA levels, especially at the beginning of school. Moreover, little is known about the longitudinal relationship between sociodemographic (e.g., gender), emotional (e.g., general anxiety), domain-general cognitive (e.g., intelligence, verbal and visuospatial working memory), domain-specific cognitive (e.g., symbolic and non-symbolic representations) variables and MA.

1.4. The current study

This longitudinal study tested children from the beginning of the first grade till the end of the second grade. Our first goal was to test whether math achievement predicts MA (Deficit Theory), MA predicts math achievement (Debilitating Anxiety Theory), or MA and math achievement have reciprocal relationships (Reciprocal Theory). Several relevant variables were considered: gender, general anxiety, fluid intelligence, verbal and visuospatial working memory, and symbolic and non-symbolic numerical representations.

The second goal of the study was to establish additional predictors of MA and math achievement in early primary school children. We tested relationships with the following variables: fluid intelligence, verbal and visuospatial working memory, symbolic and non-symbolic numerical representations, gender, and general anxiety. We expected that math achievement is predicted by fluid intelligence, verbal and visuospatial working memory, symbolic and non-symbolic numerical representations, gender, general anxiety, and MA. We also hypothesized that MA is predicted by math achievement, gender and general anxiety, fluid intelligence, verbal and visuospatial working memory, symbolic and non-symbolic numerical representations.

2. Method

2.1. Participants

Three hundred and sixty-nine children (205 girls) from 12 elementary schools (30 classes) in Kraków (Poland) were recruited for the study. None of the children were diagnosed with a math learning disability. Race, ethnicity, and language were not established because of the homogeneity of the Polish population during the time of the study. Schools were randomly selected for the study, however, a decision about participation in the project depended on schools' management and parental consent. The schools in which the study was conducted were at the top, middle, or bottom of the ranking of elementary schools in Kraków (Dolna, 2016).

There were three consecutive measurement points: T0–the beginning of the first grade, T1–the end of the first grade, T2–the end of the second grade. The number of children who completed a testing session in each measurement point was $N = 348$ at T0, $N = 317$ at T1, and $N = 263$ at T2. Drop out from the study between T0 and T2 resulted from a change of school, temporary absence, or individual decision of the child to withdraw from participation in the study. An analysis was conducted to establish whether gender, fluid intelligence, general anxiety, and math anxiety at T0 predicted participants being missing at T2. Logistic regressions were used, with each of the above variables as predictors, and status (missing/not missing) at T2 as the dependent variables. None of the variables at T0 was a significant or relevant predictor of a participant being missing at T2 (all *ps* > 0.35, all odds ratios in logistic regressions were between 1.02 and 1.07).

Mean age of children was seven years and two months ($SD = 5$ months; range = 6 years–8 years 3 months) at T0. Children were older by about +8 months at T1 and +20 months at T2. Data analysis was conducted on the 337 children for whom there was at least one observation on a dependent variable at T1 and/or T2. Missing data was addressed with full-information maximum likelihood estimation in statistical models. Although we planned to observe the relationship between MA and MATH in the third grade, the study was discontinued due to the outbreak of the COVID-19 pandemic.

2.2. Measurements

Math anxiety (MA). The modified Abbreviated Math Anxiety Scale for Elementary Children (Polish language version mAMAS-E, Szczygieł, 2019; original version mAMAS, Carey, Hill, et al., 2017) was used to measure math anxiety. mAMAS-E is a 9-item scale with satisfactory psychometric properties (Szczygieł, 2019) and is intended to evaluate math learning, math testing and total math anxiety (see Supplementary Materials, part A). The latent factor score was used as an indicator of MA in all measurements. The scale was administered to children in the form of interview. The instruction was as follows: "Do you feel math anxiety in following situation [e.g., "Thinking about a maths test the day before you take it."; "Having to complete a worksheet by yourself"]? Yes, a little, or no?", and children answered: "no" – 0 points, "a little" – 1 point, "yes" – 2 points. Children could obtain from 0 to 18 points. The higher sum of points indicates higher MA. The reliability of the mAMAS-E calculated for latent factor scores was $\alpha = 0.87$ (MA-T0), 0.85 (MA-T1), and 0.83 (MA-T2).

Math achievement (MATH). Mathematical achievements were measured via self-prepared tests (see Supplementary Materials, part A). Tasks were based on the mathematical core curriculum for elementary schools and materials recommended by the Ministry of Education in Poland. The following areas were tested: At the end of the first grade (MATH-T1): knowledge of numbers, counting, addition and subtraction, discovering rules, knowledge of money, knowledge of geometric figures, reading a tape measure. At the end of the second grade (MATH-T2): addition and subtraction, multiplication and division, reading a tape measure, spatial orientation, discovering rules, clock reading. At the end of the first and second grade, the procedure for testing math achievement was the same. Following sample tasks were used: "Sort the balloons from smallest to largest by matching them to the correct number on the strip. The letters assigned to the balloons will form a certain word. What's the word?"; "You have PLN 5. The pictures below show the money of Barbara, Wojtek and Chris. Which child has the same amount of money as you?"; "The pictures show Madeleine's dolls and Philip's knights. Which child has more toys? How much more?" Children completed tasks in written form. Researchers read-aloud instructions to avoid the impact of reading skills on mathematical performance. Testing did not have a time limit and most children completed the test in 20–40 min. The point range score for both tests was 0–62. The internal reliability tested with Cronbach's α were 0.86 (MATH-T1) and 0.91 (MATH-T2). Correlations between total score (sum of points) and each mathematical tasks were positive (T1: $r = 0.13$–0.61; T2: $r = 0.18$–0.61; $p <$ 0.05–0.001). The difficulty level was calculated as the proportion of points for correct answers to possible to obtained points. The average level of difficulty of the tasks in the two measurements was 0.76 and 0.69, respectively. Therefore, the test was easy in each grade.

Fluid intelligence (Gf). The Raven's Coloured Progressive Matrices Test (Polish language version Szustrowa & Jaworowska, 2003) was used to test fluid intelligence at the beginning of the first grade. It is a standardized thirty-six-item test with progressive level of tasks difficulty. Children choose one of the six missing pattern pieces. Regardless of the answers given, they complete the whole test. A higher sum of points in the test indicates higher Gf. Gf was measured at the beginning of the first grade and Cronbach's α was 0.80.

Verbal working memory (VWM). The WISC-R Digit Span Backward task (the Polish language edition of the Wechsler Intelligence Scale for Children – Revised; Matczak et al., 1991) was used to measure verbal working memory at the beginning of the first grade. The procedure of the test was in accordance with the test manual. Children were asked to repeat a list of spoken by researcher digits in reverse order. The list started with two elements and the number of elements increased if children successfully repeated them. Maximum of eight elements could be provided. Each span level included two lists. The session was ended if children incorrectly repeated two items consecutively. The total score was calculated by adding up the number of correctly recalled items for each list length (1 point for correct and 0 points for incorrect answer). Therefore, the minimum and maximum scores ranged from 0 to 14 points. A higher score indicates better VWM. Because of two attempts in each length, split-half reliability was calculated. We used the first trials from each span to compose the first half and the second trials to compose the second half of the test. Reliability was $r_{tt} = 0.62$ and is below the cut-off but it is due to two attempts only in the progressive test.

Visuospatial working memory (VSWM). The Corsi Block Tapping Task (Kessels et al., 2000; see Supplementary Materials, part A) was used to measure visuospatial working memory at the beginning of the first grade. The procedure of the measurement was very similar to VWM measurement. Researcher presents to children a sequence of blocks by touching them. Children were pleased to recall the presented order from last to first. Each sequence level included two attempts. If the children successively recalled, the number of items increased. Two consecutively incorrect attempts done by children finished the task. The score was calculated by sum of all correct answers (1 point for correct and 0 points for incorrect answers). The minimum and maximum scores ranged from 0 to 18 points. The split-half method was used to calculate the reliability: $r_{tt} = 0.68$. As it was in VWM, reliability is slightly below the cut-off due to a limited number of attempts and increasing the test level difficulty.

Numerical representations. The Polish language version of Numeracy Screener was used (Nosworthy et al., 2013) to measure symbolic and non-symbolic numerical magnitude processing (see Supplementary Materials, part A). Detailed information about test properties (e.g., order, ratio, density of stimuli) is placed in the authors' work (Nosworthy et al., 2013). Children compared pairs of magnitudes in two conditions: symbolic (S; 56 pairs of digits) and non-symbolic (NS; 56 pairs of dot arrays). They chose which one in each pair is larger in time by 1 min for each condition. The condition order was randomized and half of the children started from S and half of the children started from NS comparison tasks. Correct answers were scored 1 point and incorrect answers 0 points. The indicator of NS and S was calculated as a sum of points, therefore, obtainable scores ranged from 0 to 56 points in each condition. S and NS measurements were done at the beginning of the first grade. Because of the zero variance in many items, reliability is not provided.

General anxiety (GA). The Polish language version of the Revised Children's Manifest Anxiety Scale was used to test general anxiety (Stark & Laurent, 2001; Szczygieł, 2019; see Supplementary Materials, part A). It is a 7-item, unidimensional questionnaire. Children were asked about the level of their anxiety in various situations [e.g., "I am nervous when things don't go right.", "Worry something bad will happen."] using a three-point response scale (0 – "no", 1 – "a little", 2 – "yes"). The range of obtainable points was from 0 to 14. The higher sum of points indicates higher GA. The latent factor score of GA was used when testing models. The reliability of the scale was calculated on latent factor score and established at the beginning of the first grade with Cronbach's $\alpha = 0.70$.

2.3. Procedure

The measurements at T0 (September/October 2017), T1 (May/June 2018) and T2 (May/June 2019) were carried out in schools. All tasks were administered in Polish. Tested variables are presented in Table 1. The procedure in each measurement was as follows: children were tested individually by the trained researcher. The children were presented with the purpose of the study. Each child was asked for consent to participate in the study and informed about the possibility of asking questions and withdrawing from the study without any consequences. The researcher read the instructions aloud to eliminate the impact of differences in the level of the children's reading skills on the research results. The length of testing sessions was 30–40 minutes at T0 and 20–30 minutes at T1 and T2. There was no time limit in any of the measurements. Ethical permission was obtained from the the Scientific Research Ethic Committee of the Institute of Psychology of Jagiellonian University in Kraków. Some data from this longitudinal study were partially used in previous publications that had different objectives (Szczygieł, 2020; 2021; Szczygieł and Pieronkiewicz, 2022). In the current project, we analyzed following variables: T0 – MA-T0, Gf, VWM, VSWM, S, NS, GA, gender; T1 – MA-T1, MATH-T1; T2 – MA-T2, MATH-T2.

2.4. Data Analysis

Analyses were performed in the Statistica (descriptive statistics, Pearson's correlation) and *R* software (especially the "lavaan" package was used for fitting structural equation models [SEM], Rosseel, 2012). Correlation effect sizes were interpreted in accordance with following criterion: $r < 0.20$ very weak, 0.20–0.39 weak, 0.40–0.59 moderate, 0.60–0.79 strong, and >0.80 very strong correlation (Evans, 1996). Acceptable model-to-data fit indices that we adopted are following: non-significant result of χ^2 test ($p > 0.05$), CFI and NFFI >0.95, RMSEA and SRMR <0.08 (Hu & Bentler, 1999; Kline, 2016).

SEM was used to model the set of multivariate relationships among the variables of interest. Since children were clustered in 12 schools, we mean-centered all quantitative scores by school to control for a mean differences across schools. A "path analysis" approach was used, with autoregressive paths for both math achievement and MA scores across waves of measurement. We established and confirmed the longitudinal metric invariance of MA to be able evaluate structural relationships between measurements (see Supplementary Materials, part B). As three waves of data collection were available for MA, a "random intercept" factor was fitted in the initial model, as it is a preferred option to account for stability of rank-order scores in longitudinal panel models (e.g., Hamaker et al., 2015). As reported below, however, this factor had virtually zero variance and was subsequently dropped. Unfortunately, the same could not be done for math achievement as only two waves of its scores were available. Also, cross-lagged panel path regressions were fit between math achievement and MA. All other variables, which were measured at T0 and were considered as stable individual traits (Gf, VWM, VSWM, S, NS, GA, gender), had paths fitted from them to math achievement scores both at T1 and T2 and to all three waves of MA measurement. Covariances between MA and MATH at T1 and T2, respectively, were also allowed. MA-MATH cross-lagged relationship model, without predictors, is presented in Supplementary Materials, part B.

We used the Maximum Likelihood estimator with Robust standard errors and Full Information Maximum Likelihood for missing data. An exploratory model selection approach was adopted. In the "initial model" all the above listed paths were estimated freely. In the "final model", we retained only the paths that were statistically significant ($p < 0.05$) and helped to improve the model fit based on the AIC/BIC index (i.e., those paths that, if fixed to zero, caused the AIC/BIC to increase/worsen). A stepwise procedure was adopted to get from the "initial" to the "final" model. At each step/iteration, we fixed to zero that one path that caused the AIC/BIC to decrease the most, until the AIC/BIC could

Table 1
Descriptive statistics and correlation matrix between all variables.

		N	*M*	*SD*	Range	*Sk.*	*K.*	1	2	3	4	5	6	7	8	9	10	11
1	Gender	369																
2	Gf-T0	348	26.20	4.56	13–35	−0.42	−0.29	0.07										
3	S-T0	347	30.89	7.16	12–51	0.15	−0.12	0.03	0.14**									
4	NS-T0	339	31.14	7.16	12–48	−0.05	−0.22	−0.06	0.08	0.80***								
5	VSWM-T0	346	5.24	1.70	1–10	0.06	−0.04	−0.05	0.37***	0.17**	0.13*							
6	VWM-T0	345	3.41	1.16	0–8	0.28	−0.09	0.08	0.44***	0.22***	0.12*	0.34***						
7	GA-T0	349	5.74	3.32	0–14	0.24	−0.53	−0.13*	0.02	0.04	0.05	−0.02	−0.02					
8	MA-T0	347	4.30	3.84	0–18	1.00	0.77	−0.09	−0.03	−0.07	−0.04	−0.02	−0.05	0.52***				
9	MA-T1	311	2.77	3.01	0–15	1.34	1.79	−0.14*	−0.10	−0.06	−0.01	−0.07	−0.11	0.30***	0.39***			
10	MA-T2	292	3.95	3.43	0–15	0.75	−0.05	−0.17**	−0.24***	−0.12*	−0.11	−0.23***	−0.18**	0.30***	0.32***	0.50***		
11	MATH-T1	316	47.12	7.68	22–60.5	−0.69	−0.06	0.08	0.55***	0.25***	0.17**	0.38***	0.38***	0.07	−0.06	−0.11*	−0.30***	
12	MATH-T2	291	42.22	10.32	8–62	−0.59	0.11	0.07	0.50***	0.20***	0.09	0.35***	0.39***	0.02	−0.09	−0.13*	−0.30***	0.64***

Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Gender was coded as 0 – boys, 1 – girls. Gf – fluid intelligence, NS – non-symbolic numerical representation, S – symbolic numerical representation, VSWM – visuospatial working memory, VWM – verbal working memory, GA – general anxiety, MA – math anxiety, MATH – math achievement. T0 – beginning of the first grade, T1 – the end of the first grade, T2 – the end of the second grade. *N* for each pair of correlations is in Supplementary Materials, part B.

not decrease any further and/or only statistically significant paths remained (see Supplementary Materials, part B).

3. Results

3.1. Descriptive statistics

Table 1 shows descriptive statistics and the zero-order correlation matrix. MATH-T1 and MATH-T2 were strongly positively correlated with each other. MATH-T1 and MATH-T2 were moderately correlated to Gf, positively and (very) weakly related to S and NS (T1 only), positively and moderately correlated to VWM and VSWM, weakly and negatively related to MA (depends on time point of MA measurement). There were no gender differences in MATH and there were no relationships between GA and MATH.

MA was weakly/moderately and positively related to GA (T0, T1, T2), girls had higher MA than boys (T1 and T2). MA had weakly negative correlation with Gf, S, NS, VWM, VSWM (T2). MA scores were moderately positively related each other at each time point (T0, T1, T2).

3.2. Longitudinal relationship between MA and MATH

To answer whether MA predicts MATH, MATH predicts MA, or MA and MATH are related in vicious cycle, we tested an SEM model with their predictors: Gf, VWM, VSWM, S, NS, GA, gender. An additional version of the model also included a random intercept for MA to account for MA stability, but this factor had virtually no variance, $B = 0.02$, $p = .171$, so it was dropped in subsequent analyses. The model selection was conducted by fixing small standardized paths to zero one at a time, as described in the Data Analysis section. Twenty nine iterations were made until the final model was reached (see steps in Supplementary Materials, part B). The final model fitted the data very well: $\chi^2_{(31)} = 31.09$, $p = 0.462$, CFI $= 1.00$, NNFI $= 1.00$, RMSEA $= 0.003$, SRMR $= 0.032$, $N = 337$ children.

The results are as follow: MA-T0 did not predict MATH-T1, MA-T1 predicted MATH-T2 ($\beta = -0.11$, $p = 0.024$), and MATH-T1 predicted MA-T2 ($\beta = -0.14$, $p < 0.001$). These results partially support Reciprocal Theory.

3.3. Predictors of MATH and MA

Our second goal was to show predictors of MATH and MA (see Fig. 1). The results indicate that Gf-T0 ($\beta = 0.43$, $p < 0.001$), S-T0 ($\beta = 0.18$, $p < 0.001$), and VSWM-T0 ($\beta = 0.22$, $p < 0.001$) predicted MATH-T1. MATH at T2 was predicted by Gf-T0 ($\beta = 0.14$, $p = 0.01$), VWM-T0 ($\beta = 0.14$, $p = 0.003$), MA-T1 ($\beta = -0.11$, $p = 0.024$) and obviously by MATH at T1 ($\beta = 0.51$, $p < 0.001$).

MA-T0 predicted MA-T1 ($\beta = 0.66$, $p < 0.001$) and MA-T1 predicted MA-T2 ($\beta = 0.77$, $p < 0.001$). MA-T0 was predicted by GA-T0 ($\beta = 0.51$, $p < 0.001$) and S ($\beta = -0.17$, $p < 0.001$). MA-T2 was also predicted by MATH at T1 ($\beta = -0.14$, $p < 0.001$).

4. Discussion

4.1. MA and math achievement relationship

Although the negative relationship between MA and math achievement is well known, the causal relation between the two constructs is

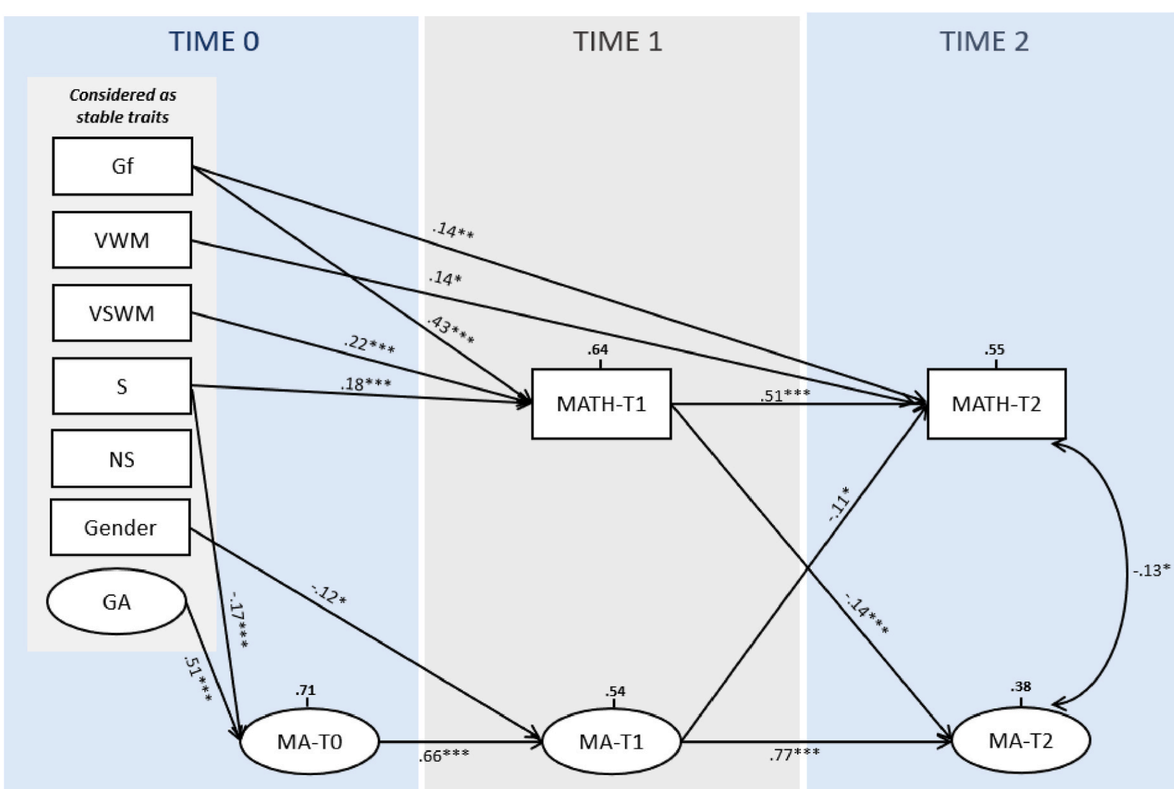

Fig. 1. The Longitudinal Relationship between MA, MATH, with Their Predictors in SEM Model
Note: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, $N = 254$. MA T0, MA T1, MA T2, MATH T1, and MATH T2 were predicted by all variables treated as stable traits in the initial model. Covariances between MA and MATH at T1 and T2, respectively, were also allowed. Significant paths in final model are presented and nonsignificant paths are hidden for clarity of the figure. Gf – fluid intelligence, NS – non-symbolic numerical representation, S – symbolic numerical representation, VSWM – visuospatial working memory, VWM – verbal working memory, GA – general anxiety, MA – math anxiety, MATH – math achievement. T0 – beginning of the first grade, T1 – the end of the first grade, T2 – the end of the second grade. MA and GA are latent factor score while other variables are observed variables.

unclear (Carey et al., 2016). Failures in mathematics may lead to higher MA (the Deficit Theory), high MA may lead to the avoidance of math learning and in turn difficulties in mathematics (the Debilitating Anxiety Theory), or a vicious circle may form between MA and math achievement (the Reciprocal Theory). In order to gain a nuanced understanding of complicated relationships, here, besides MA and math achievement we also considered many of their potential predictor variables. Our main results partially support the Reciprocal Theory showing that lower math achievement at the end of the first grade very weakly predicts higher MA at the end of the second grade and that higher MA at the end of the first grade very weakly predicts lower math achievement at the end of the second grade. Therefore, the findings are in line with previous studies conducted in middle school students (Aldrup et al., 2020; Du et al., 2021; Pekrun et al., 2017) and primary children (Gunderson et al., 2018).

As we used correlational longitudinal design, we cannot formulate claims about causality. However, thanks to the many variables we considered, we conclude that MA and math achievement most likely have a bidirectional relationship during early schooling. Similar to Gunderson et al., 2018, we observed that the path from math achievement to MA is slightly stronger than the opposite link. This suggests that young children's observation of their own learning outcomes may be crucial for MA development (Gunderson et al., 2018). Social factors may also be important contributors to the potential low math achievement to high MA pathway (Guzmán et al., 2023). Previous findings showed that children had high MA because of failures in mathematics, bad grades, negative reactions from classmates, teachers, and parents (Szczygieł & Pieronkiewicz, 2022). That is, the negative social consequences of having low math performance may contribute to increased MA. Children may associate mathematics with unpleasant experiences, and over time, avoid learning it and, consequently, may deepen math learning difficulties. In consequence, low math performance may affect math self-concept (Justicia-Galiano et al., 2017) and strengthen negative emotions towards mathematics (Carey et al., 2016; Gunderson et al., 2018). Children with higher level of MA may spend less time on solving math problems, perhaps because they want to finish the tasks as soon as possible (Morsanyi et al., 2014). In the future, they may avoid math learning and deepen their MA as a result of initial failings, and in turn have further low math achievement.

4.2. Predictors of math achievement and MA

We tested predictors of math achievement and MA in a longitudinal design. Math achievement at the end of the first grade was predicted by domain-general (fluid intelligence, visuospatial working memory) and domain-specific (symbolic numerical representation) cognitive variables measured at the beginning of the first grade. Math achievement at the end of the second grade was predicted, apart from MA at the end of the first grade, by math achievement at the end of the first grade and domain-general cognitive variables measured at the beginning of the first grade (fluid intelligence and verbal working memory).

These findings are consistent with prior studies showing that higher intelligence (Chu et al., 2016; Primi et al., 2010), better working memory (Bull et al., 2008; Soltanlou et al., 2019), and fluency in manipulating mathematical symbols (Cueli et al., 2019; Gilmore et al., 2013; Hornung et al., 2014) are related to better math achievement. However, we observed some differences in predictors of math achievement in the first and second grades. This may be due to the fact that mathematical tests in both measurements differed in the content and various cognitive processes were involved in solving these mathematical tasks (e.g., requiring retrieving facts from memory or finding relationships between tasks elements). Visuospatial working memory could be more important for first-grade math achievement due to including more pictorial and geometric-spatial tasks in comparison to test administered at the end of the second grade. Symbolic magnitude processing predicted math achievement at the end of the first grade but not second grade. These results likely appear because math achievement at the end of the first grade primarily relies on newly acquired knowledge of mathematical symbols while at the end of grade 2 already learning of other mathematical skills is more important.

Non-symbolic numerical representation, general anxiety and gender were not significant predictors of math achievement at the end of the first and second grade. First, our results regarding the role of non-symbolic numerical representation in predicting math achievement are in accordance with previous studies showing that non-symbolic skills are not significant predictors of school math achievement when domain-general cognitive abilities are taken into account (e.g., intelligence, Gross et al., 2018; cognitive control, Caviola et al., 2020; Szűcs et al., 2014). Notably, we observed stronger zero-order correlations between the symbolic numerical representation and math achievement in the first and second grades than between the non-symbolic numerical representation and math achievement. The different strengths of these (weak) correlations can be expected as the symbolic comparison task requires knowledge acquired through education. Hence, symbolic skills could be expected to be stronger correlates of school math achievement (also reliant on education) than non-symbolic numerical skills (Caviola et al., 2020). Second, we did not observe gender differences in math achievement which is consistent with some of the previous findings showing that gender differences in math performance appear later than the early school age (Bakker et al., 2019; Hutchison et al., 2019), and boys often get ahead in math in high school (Vos et al., 2023). However, it seems that gender differences in the level of math achievement depend on many factors including cultural conditions, educational systems, the presence of mathematical stereotype threat, the nature of the mathematical tasks, parental expectations and support, participants cognitive and affective characteristics, and the grade level (Breda and Napp, 2019; Lindberg, Hyde, Petersen, & Linn, 2010; OECD, 2019; Vos et al., 2023). Finally, although the meta-analysis of Caviola et al. (2022) found a weak relationship between general anxiety and math performance, here general anxiety did not predict math achievement at any time. This discrepancy may be due to the fact that the relationship may depend on situational factors, such as task difficulty, the necessity to participate in the test, and the consequences of making a mistake.

We found that stronger general anxiety at the beginning of the first grade was related to stronger MA at the beginning of the first grade. We also observed that initial MA strongly predicted further levels of MA across all waves of measurement. These results are in accordance with previous findings (Carey et al., 2017; Caviola et al., 2022) suggesting that general anxiety may serve as a precursor of MA. MA is a specific type of anxiety but is closely related to general anxiety (Carey et al., 2017; Cargnelutti et al., 2017; Hill et al., 2016). It can be hypothesized that the occurrence and the pace of development of MA depends on children's susceptibility to general anxiety. We observed gender as a predictor of MA at the end of first grade but not at other time points. Previous studies also showed inconsistent results regarding the gender gap in MA (Carey et al., 2017; Devine et al., 2012; Gierl & Bisanz, 1995; Hill et al., 2016; Ramirez et al., 2013). It is likely that children didn't know what to expect regarding math classes at the beginning of schooling, and thus both, girls and boys, revealed similar level of MA. Then, at the end of the first grade, some of the social factors like teachers or parental expectations regarding math achievement level could affect the gender gap in MA. Finally, gender differences in MA disappeared at the end of the second grade likely because including math achievement as a predictor of MA. Although prior research results suggest that MA may be related to intelligence (Schillinger et al., 2018), working memory (Pellizzoni et al., 2022), symbolic and non-symbolic numerical representations (Braham and Libertus, 2018; Lindskog et al., 2017; Pantoja et al., 2020; Skagerlund et al., 2019), our results only partially support these observations. We found that better symbolic numerical representation at the beginning of the first grade negatively and weakly predicted MA at the beginning of schooling. This result suggests that the initial level of MA may be related to knowledge about numbers. Indeed, children may start school with very diverse initial math experiences based on home numeracy activities or math activities at preschool. Other paths from domain-general and domain-specific cognitive variables to MA at all time points were nonsignificant. Zero-order correlations showed that MA was related to intelligence, verbal and visuospatial working memory and symbolic numerical representations only at the end of the second grade. These results suggest that cognitive skills may be important protective factors against negative effect of MA on math achievement when the level of math difficulty and MA increase. However, investigating this hypothesis needs further research.

It is of course possible that MA and math achievement are influenced by factors additional to the ones considered here, e.g., teaching methods (Balt et al., 2022; Gunderson et al., 2018), teachers' and parents' MA and math attitudes (Sari & Hunt, 2020), home numeracy activities (Guzmán et al., 2023), and test anxiety (Caviola et al., 2022). Indeed, although we included many cognitive and affective factors in our model, the proportion of residual variance, which is not explained, is 55%–64% in math achievement and 38%–71% in MA. These results suggest the need for further research on the predictors of both variables.

4.3. Educational implications

We found that amongst the predictors of MA at the beginning of education, the most important ones are general anxiety and the knowledge of mathematical symbols, rather than intelligence, working memory or non-symbolic numerical representation. After one year of schooling, gender differences in MA are observed and after two years of education, the level of math achievement also becomes crucial in predicting MA. In the case of math achievement, we conclude that intelligence, working memory, knowledge of mathematical symbols, and MA, rather than general anxiety and non-symbolic numerical representation, are the most important variables to focus on when preparing interventions. Additionally, our results suggest that interventions should be initiated as early as possible, as initial MA determines subsequent MA, and initial math achievement level determines subsequent math outcomes. Our study has important educational implications.

The reciprocal relationship between MA and math achievement means that educational diagnosis and interventions should be focused on both variables in parallel already during early schooling. Interventions to lower MA and develop math achievement from the beginning of schooling can affect the initial level of MA and math achievement predicts their further levels (Gunderson et al., 2018; Wang et al., 2020). Moreover, a high level of MA at the beginning of education may lower math achievement and low math scores may feed back into strengthening MA. Previous results show that enhancing math achievement and reducing MA through interventions consisting of e.g., reinterpretation of emotional arousal, expressive writing, motivating students to learn by creating a friendly atmosphere during the lesson, spatial-number, number sense, and math performance trainings, may bring beneficial effects (Sammallahti et al., 2023).

Based on the level of fluid intelligence, visuospatial or verbal working memory and symbolic numerical representation, results suggest that cognitive variables may serve as predictors of mathematical difficulties at the end of the first or second grade. Early-school screening of domain-general and domain-specific cognitive skills may effectively identify students who need special help in learning mathematics. Early identification of such students and assistance to them will help to reduce inequalities between students, which deepen during the course of education. The results of the study clearly show that the level of math achievement at the end of the second grade depends mainly on the level of math achievement at the end of the first year. Thus, supporting the development of math skills by children at the beginning of their schooling will contribute to the development of their math skills later. Conducting remedial lessons for children identified as those with lower domain-general and domain-specific cognitive abilities likely may strengthen not only math achievement but also in other areas of education. To achieve this, the cooperation of primary education teachers with school psychologists is necessary. As indicated by Gunderson et al., 2018, improving teaching methods may be important for both – MA decreasing and math achievement increasing. Indeed, our results support the view that interventions should be focused on both, as early as the first and second grade of primary school.

We observed that MA is most strongly predicted by general anxiety and the previous level of MA. In line with our findings, previous research also suggests that general anxiety may trigger MA in young children (Carey et al., 2017; Szczygieł & Pieronkiewicz, 2022). These anxieties may be related to risk of failure, task difficulty, time pressure, and fear of receiving a bad grade. Interventions for the prevention of development of MA should therefore be applied at the beginning of school, and teachers in primary education should be educated about the nature and triggers of MA and its relationship with math achievement. The fact that MA can develop especially in children with high general anxiety means that general anxiety should also be monitored at the beginning of school. Results also suggest that knowledge of mathematical symbols may predict the level of MA at the beginning of schooling. Thus, it seems that screening children's rudimentary math skills at the beginning of education may be useful to capture risk factors related to developing negative emotions about math learning. Our results also suggest that girls have higher MA than boys at the end of the first year of math education. However, this relationship disappears in the second grade, likely because math achievement starts to predict MA.

4.4. Limitations and future study directions

Our study was conducted in one large city in Poland, therefore, our conclusions may be specific to this context. While socioeconomic status is considered an important factor in determining parental interest in children's education outcomes (McLean et al., 2023; OECD, 2018b), here we did not have a relevant measure. Some children dropped out of the longitudinal study for various reasons (e.g., change of school, absence from school during measurement). While we planned to conduct measurement at the end of the third grade, the study was discontinued due to the outbreak of the COVID-19 pandemic.

To establish the relationship between MA and math achievement, we considered gender, general anxiety, fluid intelligence, verbal and visuospatial working memory, symbolic and non-symbolic numerical representations, and we also included the autoregression of MA and math achievement in the SEM model. These variables can evolve over time so it would be ideal if they could be measured at each measurement point. We are aware that other variables are also important, e.g., children's test anxiety (Wren & Benson, 2004) and cognitive control (Szűcs et al., 2014), MA and math attitude of parents and teachers (Guzmán et al., 2023; Sari & Hunt, 2020), teaching methods (Gunderson et al., 2018). Since the results of the study do not go beyond the second grade, we can only speculate that the relationships we identified will persist in later years of education. We tested MA but not math achievement at the beginning of the first grade. Further research should include parallel measurements of MA and math achievement starting from the beginning of early school education or even preschool (Petronzi et al., 2019).

We observed that the math achievement test was relatively easy for children. Therefore, we do not know if the results would look similar if the math test were more demanding and under done time pressure. Subsequent research could also consider the various dimensions of MA and different types of math skills. Because the tasks and scales were short and had a limited range of responses/attempts, the reliability of some of the tasks was borderline or slightly below acceptability. Regarding self-report measures, it should also be noted that children's understanding of items or response scales may vary. Therefore, a particular challenge for further research among children is preparing short, ecologically valid and reliable measurement tools.

5. Conclusion

Our study supports the Reciprocal Theory of the MA and math achievement relationship showing that lower math achievement at the end of the first grade predicts higher MA at the end of the second grade and that higher MA at the end of the first grade predicts lower math achievement at the end of the second grade. Our study indicates that important predictors of MA are general anxiety and knowledge of numbers (the beginning of education), the previous level of MA and gender (the end of the first grade), and the previous level of MA and math achievement (the end of the second grade). This pattern of results suggests that the main factors responsible for MA in the early years of school are a tendency to a higher level of general anxiety, especially visible in girls, and mathematical knowledge. Domain-general (fluid intelligence and verbal and visuospatial working memory) and domain-specific factors (non-symbolic numerical representation) are not the main factors in the development of MA, although they may protect students against developing MA by positively influencing the development of mathematical skills. Math achievement at the end of the first and second grade was predicted by domain-general (intelligence and working memory) and domain-specific (symbolic numerical representations) cognitive variables and by MA at the end of the second grade. Such results suggest that both cognitive and emotional factors are important in predicting level of math performance at the beginning of school and should be considered together in future studies. Further research should also focus on the relationship between MA and math achievement in a longitudinal design and on the numerous individual and social variables that should be controlled for.

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CRediT authorship contribution statement

Monika Szczygieł: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Denes Szűcs:** Writing – original draft, Writing – review & editing. **Enrico Toffalini:** Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.learninstruc.2024.101906.

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