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Cognitive and Emotional Math Problems Largely Dissociate: Prevalence of Developmental Dyscalculia and Mathematics Anxiety

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A negative correlation between math anxiety and mathematics performance is frequently reported. Thus, some may assume that high levels of mathematics anxiety are associated with poor mathematical understanding. However, no previous research has clearly measured the association between mathematics anxiety and mathematical learning disability. To fill this gap, here we investigated the comorbidity of developmental dyscalculia (a selective, serious deficit in mathematical performance) and mathematics anxiety in a sample of 1,757 primary school (8- to 9-year-old) and secondary school (12- to 13-year-old) children. We found that children with developmental dyscalculia were twice as likely to have high mathematics anxiety as were children with typical mathematics performance. More girls had comorbid mathematics anxiety and developmental dyscalculia than did boys. However, 77% of children with high mathematics anxiety had typical or high mathematics performance. Our findings suggest that cognitive and emotional mathematics problems largely dissociate and call into question the assumption that high mathematics anxiety is exclusively linked to poor mathematics performance. Different intervention methods need to be developed to prevent and treat emotional and cognitive blocks of mathematical development.

Educational Impact and Implications Statement
This study shows that about one fifth of children meeting criteria for developmental dyscalculia are also highly anxious about mathematics. Yet, the majority of children with high mathematics anxiety have adequate or even high mathematics performance. These findings suggest that for the most part, each of these math learning problems needs to be treated separately; interventions targeted toward reducing or offloading worrying thoughts may be beneficial to children with math anxiety, whereas interventions focusing on improvement of numerical skills and working memory are more likely to be successful in the treatment of developmental dyscalculia.

Keywords: developmental dyscalculia, math anxiety, gender differences

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In today's information age, mathematical skills are becoming as important for everyday life and employment as is literacy. However, cross-national research has revealed that around 6% of children have problems acquiring mathematical skills (reviewed in Devine, Soltész, Nobes, Goswami, & Szűcs, 2013). Mathematical learning impairments of developmental origin are usually termed *mathematical learning disability* (MLD) or *developmental dyscalculia* (DD). Mathematics anxiety (MA), on the other hand, refers to a debilitating negative *emotional* reaction to mathematical tasks, which may occur in children and adults with and without mathematics learning disabilities (Ashcraft, 2002). It is important to note that children affected by MA may come to develop negative attitudes toward mathematics, avoid or drop out of mathematics classes, or stay away from careers involving quantitative skills (Ashcraft, 2002; Ma, 1999). Much research has focused on the correlation of MA and mathematics performance across the ability spectrum (e.g., Carey, Hill, Devine & Szűcs, 2016; Hembree, 1990; Ma, 1999), but little research has specifically investigated the association between MA and performance within mathematical disability subgroups or the prevalence of comorbidity of MA and DD. Many studies have revealed a moderate overall correlation between MA and mathematics performance (approximately $r = -.30$; e.g., Hembree, 1990; Ma, 1999). Thus, because MA is associated with lower mathematics performance, some may assume that high MA is strongly linked to poorer mathematical

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skills, that is, that MA is just another term for low mathematics ability (Beilock & Willingham, 2014). However, to our knowledge, no prior research has investigated the prevalence of comorbidity of MA and DD. Furthermore, research investigating the link between MA and mathematics performance in children and adolescents with DD is sparse. Past research has tended to show that girls report higher MA than do boys, particularly at the secondary school level (Devine, Fawcett, Szűcs, & Dowker, 2012; Hill et al., 2016). However, it is currently unknown whether girls are also more likely to be affected by comorbid MA and DD than are boys. The current study aims to fill these research gaps by jointly investigating MA and DD, and inspecting gender differences, in 1,757 English primary and secondary school students.

Developmental Dyscalculia (DD)

Children with DD lag behind their peers in mathematics performance, but otherwise their general cognitive ability, reading, and writing skills are normal (Butterworth, 2005). The causal origins of DD are unknown, but several existing theories suggest that DD is related to the impairment of one or many possible cognitive functions–representations, for example, magnitude representation, working memory, inhibition, spatial skills, or phonological ability (Szűcs & Goswami, 2013). Specific criteria for clinical diagnosis of DD are provided in the *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; *DSM–5;* American Psychiatric Association, 2013) and the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD–10), known as "specific disorder of arithmetical skills" (World Health Organisation, 1992, p. 194). Both of these diagnostic taxonomies stipulate that for children to be diagnosed with DD, their mathematics abilities (as measured by standardized tests) must be significantly below the level expected for their age and should not be due to general intellectual disability or inadequate educational provision. However, neither the *DSM–5* nor the ICD–10 clinical diagnostic criteria define a specific diagnostic threshold for low mathematics performance. Furthermore, there are some differences between the *DSM–5* and ICD–10 criteria regarding the persistence and specificity of the difficulties and the sources of evidence required for diagnosis.

In any case, clinical diagnostic criteria are not consistently employed in DD research studies (Devine et al., 2013). For example, many researchers define DD operationally if individuals have lower mathematics performance than the average performance for their age, but the inclusion of a control variable (e.g., reading, spelling, IQ) varies across studies. Moreover, the mathematics performance cutoff used for identification of DD in research varies considerably across international studies (from performance below the 3rd percentile to performance below the 25th percentile (2 *SD*s to .68 *SD* below the mean). Other DD inclusion criteria have been employed in research, criteria such as a discrepancy definition (e.g., between mathematics performance and performance on a control variable such as IQ or language abilities), a 2-year achievement delay (i.e., performance below the mean performance of the school grade 2 years below), or resistance to intervention (reviewed in Devine et al., 2013). The choice of inclusion criteria necessarily impacts the sample that is selected; thus, the prevalence estimates reported for DD in previous prevalence studies range between 1.3% and 13.8% depending on the criteria used (Devine et al., 2013). Two studies have estimated the prevalence of DD in the United Kingdom (U.K.) previously. Lewis and colleagues assigned children to the DD group if their mathematics performance was below 1 *SD* below the mean and reading and IQ performance was at or above a standardized score of 90 (slightly above 1 *SD* below the mean) and found that 1.3% of their sample met these inclusion criteria (Lewis, Hitch, & Walker, 1994). More recently, Devine et al. (2013) investigated the effects of using different DD definitions on the prevalence of DD and gender differences. When DD was defined as mathematics performance below 1 *SD* below the mean and reading performance at or above 1 *SD* below the mean, 6% of their sample met the criteria for DD.

Mathematics Anxiety (MA)

MA is broadly defined as a state of discomfort caused by performing mathematical tasks (Ma & Xu, 2004a, 2004b). MA can be manifested in many different ways, for example as feelings of apprehension, dislike, tension, worry, frustration, and fear (Ashcraft & Ridley, 2005; Ma & Xu, 2004, 2004b; Wigfield & Meece, 1988). MA is positively correlated with anxiety elicited by testing situations (test anxiety; Hembree, 1990: $r = .52$; Kazelskis et al., 2000: $r = .50$ for male individuals, $r = .52$ for female); however, it is considered a distinct construct (Ashcraft & Ridley, 2005). Similar to test anxiety, MA is multidimensional. For example, Wigfield and Meece (1988) identified two dimensions that correspond to those identified for test anxiety (Liebert & Morris, 1967): a cognitive component (usually referred to as "worry"), which concerns worries about performance, and an affective component ("emotionality"), which describes nervousness or tension and associated physiological reactions felt in evaluative settings (Dowker, Sarkar, & Looi, 2016). Some MA scales separate MA elicited by testing situations from other types of MA (e.g., manipulating numbers, doing arithmetic, or using mathematics in everyday life; Pletzer, Wood, Scherndl, Kerschbaum, & Nuerk, 2016). The Abbreviated Math Anxiety Scale (AMAS), for example, consists of two subscales measuring (a) MA felt when learning mathematics in the classroom (Learning MA) and (b) MA felt in testing situations (Evaluation MA; Hopko, Mahadevan, Bare, & Hunt, 2003).

Although MA is present in younger school children (Aarnos & Perkkilä, 2012; Chiu & Henry, 1990; Newstead, 1998; Ramirez, Gunderson, Levine, & Beilock, 2013), MA and negative attitudes toward mathematics appear to increase at the secondary school level (Blatchford, 1996; Dowker, 2005) and persist into postsecondary education and adulthood (Betz, 1978; Jameson & Fusco, 2014). Nonetheless, few researchers have systematically estimated the prevalence of MA.

It is important to note that academic anxieties such as MA are not considered clinical anxiety disorders (e.g., specific phobia), nor are academic anxieties currently recognized in the *DSM–5* or the ICD–10 (American Psychiatric Association, 2013; World Health Organisation, 1992). Questionnaires alone cannot be used to diagnose specific phobia (American Psychiatric Association, 2013; World Health Organisation, 1992); however, they are used extensively in educational and psychological research for identifying MA and test anxiety in children and adults.

Many different self-report questionnaires have been developed over the years to measure trait MA. The most frequently used scale is the Mathematics Anxiety Rating Scale (MARS), which has 98 items (Richardson & Suinn, 1972). However, with such a large number of items, the MARS is time consuming to complete. Thus, several shorter questionnaires have been developed, including scales specifically for use with primary school children (see Dowker et al., 2016, for a review). Although these other child-friendly scales have reported good reliability, they are typically suitable for use with only a specific age range and have often been validated with only American samples (Carey, Hill, Devine, & Szűcs, 2017). Devine et al. (2012) and Zirk-Sadowski, Lamptey, Devine, Haggard, and Szűcs (2014) recently modified Hopko and colleagues' nine-item AMAS (Hopko, et al., 2003) for use with British primary and early secondary school students. With only nine items, the modified AMAS (hereafter, mAMAS) is suitable for administration with younger school children yet has good reliability and construct validity (Carey et al., 2017; Zirk-Sadowski et al., 2014).

Similar to DD research, MA researchers utilize different definitions of high MA. Ashcraft and colleagues defined high MA as scores falling above 1 *SD* above the mean MA level (Ashcraft, Krause, & Hopko, 2007); assuming MA scores are normally distributed, a cutoff at 1 *SD* above the mean would indicate that approximately 17% of the population would meet the criteria for being highly math anxious. Yet, the distribution of MA scores is often not reported, making the use of an *SD* definition of high MA questionable. According to other definitions, the prevalence of high MA could be much lower. Chinn defined high MA as scores at or above a score of 60 on Chinn's mathematics anxiety survey, which corresponds to "often anxious" in mathematics situations, and found that between 2% and 6% of secondary school students were affected by high anxiety (Chinn, 2009).

Gender Differences in DD and MA

Although boys are overrepresented in some developmental disorders, such as reading disability, dyslexia, ADHD, and autistic spectrum disorder (Bauermeister et al., 2007; Rutter et al., 2004; Scott, Baron-Cohen, Bolton, & Brayne, 2002), the gender ratio reported in past studies of DD is not consistent. Some studies have reported that DD is more prevalent in girls (e.g., Dirks, Spyer, van Lieshout, & de Sonneville, 2008; Hein, Bzufka, & Neumärker, 2000; Lambert & Spinath, 2014; Landerl & Moll, 2010) or boys (e.g., Barahmand, 2008; Reigosa-Crespo et al., 2012; von Aster, 2000), yet U.K. studies have reported that DD is equally prevalent in both genders (Devine et al., 2013; Lewis et al., 1994). Studies have shown that secondary school girls and female adults tend to report higher levels of MA than do secondary school boys and male adults (e.g., Chang & Cho, 2013; Devine et al., 2012; Else-Quest, Hyde, & Linn, 2010; Ferguson, Maloney, Fuselsang, & Risko, 2015; Frenzel, Pekrun, & Goetz, 2007; Goetz, Bieg, Lüdtke, Pekrun, & Hall, 2013; Primi, Busdraghi, Tomasetto, Morsanyi, & Chiesi, 2014). However, MA gender differences are less consistent at the primary school level (see Hill et al., 2016, for a review). Thus, there appears to be some inconsistency across studies regarding gender differences in DD prevalence and MA gender differences at the primary school level. Several factors could explain these conflicting findings, factors including variation in the selection criteria employed, the measures of both mathematics performance and MA used, and the sociocultural context of the samples under study (see Birgin, Baloğlu, Çatlıoğlu, & Gürbüz, 2010; Devine et al., 2012, 2013; Else-Quest et al., 2010, for discussion of these issues).

Relation Between MA and Performance/DD

As mentioned, studies have revealed moderate negative correlations between MA and performance ($r \sim -.30$; Hembree, 1990; Ma, 1999), and meta-analytic research has confirmed this negative association exists across many nations and cultures (Lee, 2009). Many studies have focused on the direction of this relationship, with the aim of determining whether MA has debilitating effects on performance or whether prior poor performance leads to the development of MA (Carey et al., 2016). The former direction has been labeled the *debilitating anxiety* model, whereas the latter is referred to as the *deficit theory* (Carey et al., 2016). The deficit theory claims that anxiety emerges as a result of an awareness of poor mathematics performance in the past (Tobias, 1986). In contrast, the debilitating anxiety model posits that high levels of anxiety interfere with performance due to a disruption in preprocessing, processing, and retrieval of information (Carey et al., 2016; Tobias, 1986; Wine, 1980). This model also argues that "MA may influence learning by disposing individuals to avoid mathematics-related situations" (Carey et al., 2016, p. 2; Chinn, 2009; Hembree, 1990).

The deficit theory is supported by research showing that children with MLD show higher levels of MA than do children with typical mathematics performance (Lai, Zhu, Chen, & Li, 2015; Passolunghi, 2011; Wu, Willcutt, Escovar, & Menon, 2014). Moreover, research has suggested that the association between MA and arithmetic problem solving is stronger in children with DD than in children without DD (Rubinsten & Tannock, 2010). Children's mathematics performance has been shown to predict their MA levels in subsequent school years (Ma & Xu, 2004, 2004b), providing further support for the deficit theory. Other research has revealed deficits in basic numerical processing in highly math-anxious adults (Maloney, Ansari, & Fugelsang, 2011; Maloney, Risko, Ansari, & Fugelsang, 2010); however, it is unclear whether these deficits are a cause or a consequence of MA. That is, highly math-anxious adults' basic numerical abilities may be impaired because they have avoided mathematical tasks throughout their education and adulthood due to their high levels of MA, which would be more in line with the debilitating anxiety model (Carey et al., 2016).

Support for the debilitating anxiety model comes from studies that have shown that adults and adolescents with high MA tend to avoid math-related situations, avoiding enrolling in mathematics classes or taking up careers involving mathematics (Hembree, 1990). Adults with high MA have been shown to have decreased response times and increased error rates (Ashcraft & Faust, 1994) and decreased cognitive reflection during mathematical problem solving (Morsanyi, Busdraghi, & Primi, 2014), suggesting that math-anxious adults tend to avoid processing mathematical problems. Further support for the debilitating anxiety model comes from studies indicating that processing resources used for mathematics problem solving are taxed by MA. For example, negative relationships have been found between MA and working memory span (Ashcraft & Kirk, 2001), and the effects of high MA on performance have appeared to be more marked for math problems with a high working memory load (Ashcraft & Krause, 2007). The debilitating anxiety model is also supported by studies that have shown that performance is affected when MA is manipulated (e.g., Park, Ramirez, & Beilock, 2014) or that the association between MA and performance is reduced when tests are completed in a more relaxed format (Faust, Ashcraft, & Fleck, 1996). Additional support for the debilitating anxiety model comes from studies that have manipulated stereotype threat (thought to increase anxiety in girls and female adults) and found effects on performance and from neuroimaging studies that have suggested links between MA, performance, and different brain regions involved in both numerical and emotional processing (e.g., Beilock, Rydell, & McConnell, 2007; Lyons & Beilock, 2012; Pletzer, Kronbichler, Nuerk, & Kerschbaum, 2015; but also see Carey et al., 2016, for a detailed review).

Thus, the evidence supporting the two models has been in conflict. The purported mechanisms proposed by each model may contribute to this conflict (Carey et al., 2016). That is, longitudinal studies may be more likely to support the deficit theory because knowledge of poor performance is likely to lead to increased anxiety over time, whereas the mechanisms thought to be involved in the debilitating anxiety model are likely to impact performance in the short term and, thus, are more likely to be supported by experimental studies. Therefore, the two models may, in fact, operate simultaneously (Carey et al., 2016). Alternatively, in some individuals, experiences of failure or negative evaluations in mathematics may lead to an increase in MA, possibly resulting in a vicious circle, which also leads to an ever-increasing MA–performance relationship (Carey et al., 2016; Devine et al., 2012; Jansen et al., 2013). This bidirectional relationship between MA and performance has been labeled the *reciprocal theory* (Carey et al., 2016). Indeed, longitudinal data have suggested that the MA and math performance relationship functions reciprocally. Luo and colleagues found that MA levels were linked to students' prior achievement and that MA, in turn, was linked to future performance (Luo et al., 2014). Similarly, Cargnelutti and colleagues found similar evidence for a bidirectional relationship between MA and performance in young children (Cargnelutti, Tomasetto, & Passolunghi, 2017).

Despite this large body of literature investigating the relationship between MA and performance, crucially, no prior research has investigated the prevalence of comorbidity of MA and DD. Previous studies have compared MA levels in different mathematics achievement groups (e.g., Lai et al., 2015; Passolunghi, 2011; Wu et al., 2014) or have compared the working memory profiles of children with MA and DD (e.g., Mammarella, Hill, Devine, Caviola, & Szűcs, 2015); however, the prevalence of children with comorbid DD and high MA was not reported, nor was the correlation between MA and mathematics performance reported separately in the different achievement groups. Prior investigations of DD prevalence in U.K. samples did not also measure MA (e.g., Devine et al., 2013; Lewis et al., 1994); thus, it is not currently clear what percentage of children are affected by these mathematics learning problems in combination. Moreover, the gender ratio of comorbid DD and MA is unknown. The current study aimed to fill these research gaps by measuring the comorbidity of MA and DD in a large sample of primary and secondary school children. This study is the first phase of a larger investigation of the early experiences of MA in British school children. In the current analysis, we first estimated the prevalence of DD and MA and the comorbidity of DD and MA. We used an absolute threshold definition of DD used in a recent U.K. study by Devine et al. (2013) and thus expected to replicate the prevalence rate of 6% reported there. However, we had no a priori definition of high MA and thus derived our estimate of high MA prevalence and prevalence of MA and DD comorbidity from observation of the MA score distribution. Furthermore, we compared the proportion of high MA children falling in different mathematics performance groups (those with typical mathematics performance, DD, and comorbid mathematics and reading difficulties). Informed by previous research (Lai et al., 2015; Passolunghi, 2011; Wu et al., 2014), we expected that children with DD would be more likely to have high MA than would children with typical mathematics performance. We also inspected gender differences in MA, DD, and co-occurring DD and MA. We expected to find, in line with previous U.K. studies (Devine et al., 2013; Lewis et al., 1994), no gender difference in DD prevalence. However, we had no hypothesis regarding gender differences in the prevalence of comorbidity of MA and DD, due to the lack of prior research investigating this.

Method

Participants

The sample consisted of 1,757 children and adolescents attending primary and secondary schools in southeast England. The primary school sample ($N = 830$) consisted of 408 girls and 422 boys from Grade 4 (mean age = 109.4 months; $SD = 3.73$). The secondary school sample ($N = 927$) consisted of 340 girls and 349 boys from Grade 7 (mean age = 146.93 months; $SD = 3.54$) and 120 girls and 118 boys from Grade 8 (mean age = 151.26 months; $SD = 3.45$). Note that school grades given here are not equivalent to U.S. school grades. School demographics varied widely, with locations being both urban and rural. A school's percentage of students receiving free school meals (FSM) can be used as an indicator of socioeconomic status, because consistent economic criteria are used nationwide to determine a child's entitlement to FSM (Gorard, 2012). Schools in this sample varied from 2.9% to 36.5% receiving FSM (Department for Education, 2015b), with schools falling both above and below the national average (calculated as 20.9% of 11-year-olds in 2014, from figures in Department for Education, 2015a). Schools also varied widely in the percentage of students with special educational needs (SEN) and who had English as an additional language (EAL). Students were not excluded on the basis of SEN or EAL, to increase the representativeness of the sample. Parental consent was received for all children before testing. The study received ethical permission from the Psychology Research Ethics Committee of the University of Cambridge. The study was carried out in accordance with the approved guidelines of the ethics committee.

Materials

Math anxiety. Math anxiety was measured using the mAMAS (Devine et al., 2012; Zirk-Sadowski et al., 2014), a version of the nine-item AMAS self-report questionnaire (Hopko et al., 2003) that was modified for British students. Although the AMAS is a short scale, research has indicated that it is as effective as the longer MARS (Hopko, 2003; e.g., internal consistency: Cronbach's alpha = .90; 2-week test–retest reliability: $r = .85$; convergent validity of AMAS and MARS-R: $r = .85$). Participants indicated how anxious they would feel during certain situations involving math on a 5-point Likert scale to ranging from 1 (*low anxiety*) to 5 (*high anxiety*). The maximum score is 45.

The mAMAS was used previously with a large sample of British primary school children (Zirk-Sadowski et al., 2014). Further research determined that the mAMAS retains the factor structure of the original scale (Carey et al., 2017). The modifications involved minor adjustments to British English and terminology and the replacement of items because some of the AMAS items referred to advanced topics that would not be meaningful to primary or lower secondary school children (Ashcraft & Moore, 2009). For example, "Checking the tables in the back of a textbook" was changed to "Completing a worksheet by yourself" (see the Results section for reliability estimates of the mAMAS in the current sample; the mAMAS can be found in the Appendix).

Mathematics performance. Students' math performance was assessed using the Mathematics Assessment for Learning and Teaching tests (MaLT; Williams, 2005). These group-administered pencil-and-paper tests were developed in line with the National Curriculum and National Numeracy Strategy for England and Wales (Williams, Wo, & Lewis, 2008). Items cover a range of mathematical content, such as counting and understanding numbers, knowing and using number facts, calculating, understanding shape and measurement, and handling data. In accordance with their schooling level, Grade 4 students completed the MaLT 9, Grade 7 students completed the MaLT 12, and Grade 8 students completed the MaLT 13. Students had 45 min to complete the tests. The tests were age-standardized using a nationally representative sample of 12,591 children from 120 schools across England and Wales, and all show good internal consistency (MaLT 9: $\alpha = .93$, MaLT 12: $\alpha = .92$, MaLT 13: $\alpha = .93$).

Reading performance. The Hodder Group Reading Tests II (HGRT-II; Vincent & Crumpler, 2007) were used to assess students' reading performance. The written tests include multiple-choice items that assess children's ability to read and understand words, sentences, and passages. Each test has two parallel versions, and we used these to discourage students from copying each other. In accordance with their schooling level, Grade 4 students completed the HGRT-II Level 2, and Grades 7 and 8 students completed the HGRT-II Level 3. Students had 30 min to complete the tests. The tests were standardized in 2005 with children from 111 schools across England and Wales (HGRT-II Level 2: $\alpha = .95$, HGRT-II Level 3: $\alpha = .94$).

Procedure

Researchers went to schools to administer the tests and questionnaires. Children were assessed in group settings (either as a class or a whole year group) with sessions lasting approximately 2 hr. The order in which the mAMAS, MaLT, and HGRT-II were administered was counterbalanced between schools.

Given the young age of the primary school students, we made sure to present the testing material in a child-friendly and accessible manner. We presented practice questionnaire items written by the authors (e.g., "Rate how anxious you would feel climbing a tree") alongside a colorful PowerPoint slide show. Furthermore, we defined or explained any difficult words or terms (e.g., *anxiety* was defined as "nervousness" and "worry"), and researchers checked that children understood how to complete the practice items before proceeding with the mAMAS. All mAMAS items were read out loud. The questionnaire was formatted so that it was more readable for young children and included sad and happy emoticons at the end points of the Likert scale to aid students in their responses (see the Appendix). However, the researchers emphasized that the questionnaire was assessing anxiety and that the faces in this context were meant to indicate feeling less and more anxious, not happiness and sadness.

Grouping of Children

When we use the term *all children,* we are referring to the whole sample. In line with Devine et al. (2013), DD was defined as mathematics performance below 1 *SD* below the mean and reading performance as above 1 *SD* below the mean. Comorbid mathematics and reading difficulties (hereafter, DD + RD) was defined as mathematics and reading performance below 1 *SD* below the mean. Children with typical mathematics (TM) performance had mathematics performance at or above 1 *SD* below the mean.

Data Analysis

Although the mAMAS consists of separate Learning MA and Evaluation MA components, in the current study we focused on only total MA scores. The normality of the distribution of MA scores for all children was tested using the Shapiro–Wilk test. Chi-square analysis was used to compare the frequency of girls and boys with DD, the frequency of DD in the three year groups, and the frequency of girls and boys with high MA and DD.

The association between MA and performance in the whole sample and in students with DD was measured using Spearman's rank correlation. To further assess the robustness of correlations, we also constructed bias-corrected and accelerated 95% bootstrap confidence intervals for correlations (hereafter, 95% BcaCI).

The normality of the MA distribution in DD children was tested using the Shapiro–Wilk test, and the distributions for each gender were compared using the Mann–Whitney *U* test. Internal consistency was estimated using Cronbach's alpha coefficient and ordinal alpha coefficients. MA raw scores were sorted into 5 bins. Where distributions differed, the cell counts of girls and boys with DD were compared using chi-square analyses. In comparisons with sample sizes of less than five, Fisher's exact *p* is reported. Chi-square analyses were also used to compare the frequency of children with high MA in different mathematics ability groups. Effect sizes for chi-square analyses are reported (φ). Analyses were done in MATLAB 8.5 (MATLAB, 2015), and in R (R Core Team, 2016) using the *GPArotation, psych,* and *Rcmdr* packages (Bernaards & Jennrich, 2005; Fox, 2005; Revelle, 2013). Power calculations were done in G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009).

Results

Prevalence of High MA

We inspected the distribution of raw MA scores to determine whether a statistical definition of high MA could be used, a definition such as that used by Ashcraft et al. (2007): MA scores greater than 1 *SD* above the mean. As shown in Figure 1A, the

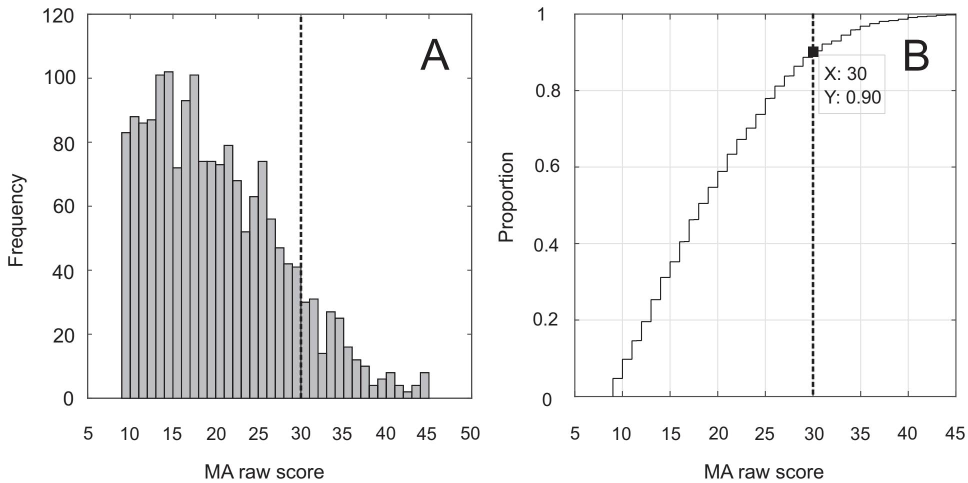

Figure 1. The distribution of raw mathematics anxiety (MA) scores (Panel A) and the cumulative distribution function of MA scores (Panel B) among primary and secondary school children. The 90th percentile (denoting high MA cutoff) is shown by the dashed line.

distribution of mAMAS scores in the current study was significantly different from normal (N = 1,757; W = .95; $p < .001$; skewness = .70; kurtosis = −.006; see the online supplemental materials for further details about nonnormality of the mAMAS). However, none of the subsequent analyses required normality of MA scores. We defined high MA as scores at or above the 90th percentile, which corresponded to raw scores of 30 and above (an average score above *Moderate amount of anxiety* on the scale). Figure 1B shows the empirical cumulative distribution function with the score corresponding to the 90th percentile marked (the percentiles corresponding to each raw score are also provided in tabular format in the online supplemental materials). We note that the actual percentage of children identified as having high MA was 11% of the whole sample, because the precise location of the 90th percentile fell within a group of several children with scores of 30. Rather than arbitrarily selecting some of the children with scores of 30 to get a high MA group of exactly 10% of the sample, we included all children with scores of 30 in the high MA group, and thus, the final percentage was 11%.

Cronbach's alpha for the mAMAS was .85 (primary sample α = .85; secondary sample α = .86), and split-half reliability was .84 (primary sample = .85; secondary sample = .86). Cronbach's alpha tends to underestimate reliability in cases where data are not continuous (e.g., Likert-type scales), when there are few items in a scale, and when scores are not normally distributed (these issues are discussed in Cipora, Szczygieł, Willmes, & Nuerk, 2015). Therefore, in line with Cipora et al. (2015), we estimated the reliability of the mAMAS further using ordinal alpha coefficients (Gadermann, Guhn, & Zumbo, 2012). Ordinal alpha for the mAMAS was .89 (.89 for primary school students and .89 for secondary school students). Ordinal alpha did not increase if any item was dropped. Thus, the mAMAS demonstrated good reliability at both school levels.

Prevalence of DD

To determine the prevalence of comorbidity of DD and MA, we first inspected the prevalence of DD in the sample. Using the absolute threshold definition of DD used by Devine et al. (2013), we included 99 children (5.6%) in the group of children with DD. The number and percentage of children in the DD group by gender and grade are presented in Table 1. Chi-square analysis confirmed that the number of girls and boys in the DD group was not significantly different, $\chi^2(df = 1, N = 1757) = 1.82, p = .18; \varphi = .032$. There were more children with DD in Grade 4 than in Grade 7, $\chi^2(df = 1, N = 1519) = 6.52, p = .012; \varphi = .065$; however, the number of children with DD was not significantly different between Grades 4 and 8, $\chi^2(df = 1, N = 1068) = .046, p = .831; \varphi = .007$, nor between Grades 7 and 8, $\chi^2(df = 1, N = 927) = 4.54, p = .033; \varphi = .069$, after correction for multiple comparisons (p value of .05; divided by the number of comparisons: three comparisons).

Relation Between DD and MA

In the whole sample of 1,757 children, MA was significantly and negatively correlated with mathematics performance ($r_s = -.30, p < .001$, 95% BcaCI [−.34, −.25]). The correlation between MA and mathematics performance is shown in Figure 2A. The correlation between MA and mathematics performance in the TM group was also significant ($r_s = -.28, p < .001$, 95% BcaCI [−.33, −.24]). In contrast, the correlation between MA and mathematics performance within the DD group was not significant ($r_s = -.09, p = .38; n = 99$;

Table 1
Primary and Secondary School Children in the Developmental Dyscalculia Group by Gender and Grade

	Girls		Boys		Total	
Grade	*n*	%	*n*	%	*N*	%
Grade 4	31	7.6	25	5.9	56	6.7
Grade 7	17	5.0	9	2.6	26	3.8
Grade 8	9	7.5	8	6.7	17	7.1
Total	57	6.5	42	4.7	99	5.6

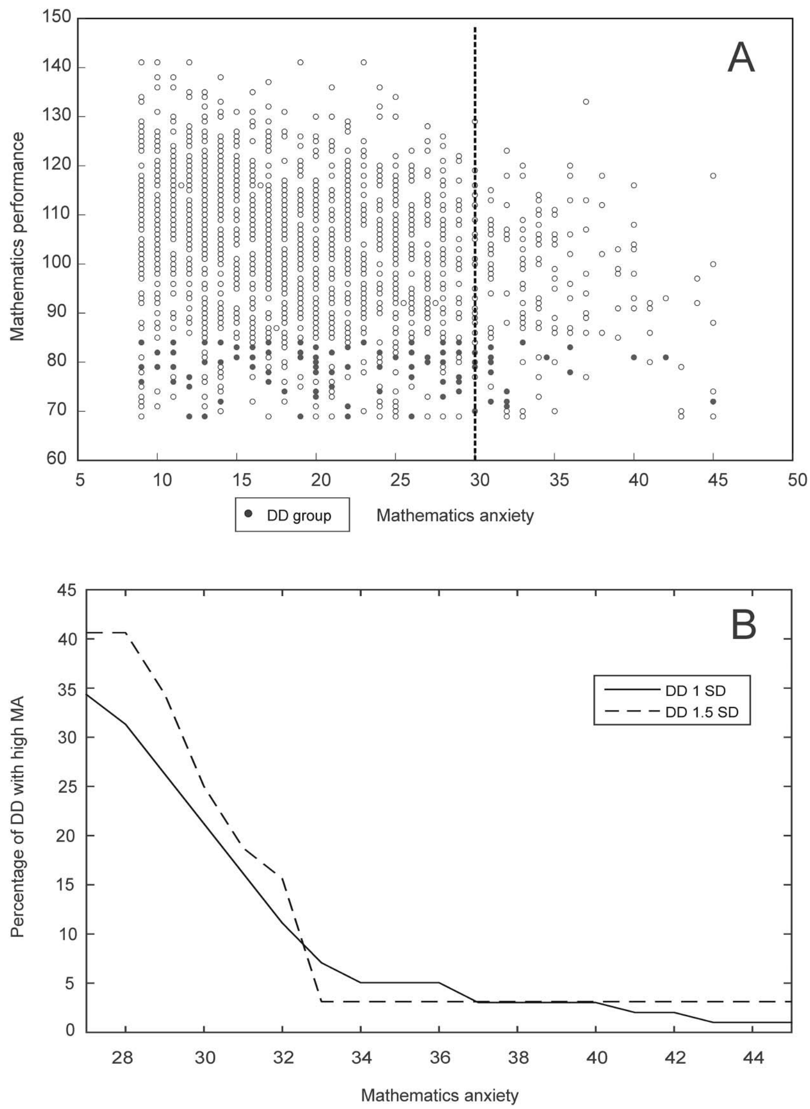

Figure 2. Panel A: The correlation between mathematics anxiety (MA) and mathematics performance in the whole sample. The high MA cutoff is denoted by the dashed line. Filled circles show children in the developmental dyscalculia (DD) group (mean −1 *SD* definition). Panel B: The percentage of DD children with high MA using different DD inclusion criteria (math performance below 1 *SD* below the mean vs. 1.5 *SD* below the mean; note that both criteria include average reading performance) and different MA cutoffs (raw scores between 27 and 45: the maximum MA raw score).

95% BcaCI [−.29, .12]), nor was the correlation significant within the DD + RD group ($r_s = -.02$, $p = .79$; $n = 140$; 95% BcaCI [−.19, .14]). Note that the lack of correlation in these subsamples was not due to lack of power, because the power to detect a correlation of $r_s = -.30$ in these groups was .93–.95; the lack of correlation in such subsamples can be expected because of the narrow range of mathematics scores in the DD and DD + RD groups. The DD group among the whole sample is also shown in Figure 2A, and the lack of correlation between MA and mathematics performance in this group can be seen. Note that the spread of MA scores has about the same range in the DD group as in the whole sample.

Prevalence of Comorbidity of DD and High MA

Table 2 shows the percentage of students with high MA in the different mathematics performance groups. When using a threshold of high MA at or above the 90th percentile, 10% of students with typical mathematics performance had high MA; however, 22% percent of students in the DD group had high MA. Note that this percentage is of the children who met the DD criteria, not the percentage of all children with math scores falling below 1 *SD* below the mean. The frequency of children with high MA was significantly different between the DD group and the TM group, $\chi^2(df = 1, N = 1617) = 14.42$, $p < 001$; $\varphi = .094$. The frequency of children with high MA

Table 2
Math Anxiety (MA) Variables by Group for Primary and Secondary School Children

Variable	DD + RD		DD		TM		Whole sample	
	n	%	*n*	%	*n*	%	*N*	%
Proportion with high MA within each group	24/140	17	22/99	22	152/1,518	10	198/1,757	11
Proportion relative to all high MA children	24/198	12	22/198	11	152/198	77		
Mdn	23		22		18		18	
95% BcaCI	[21, 24]		[20, 26]		[17, 18.67]		[18, 19]	

Note. DD = developmental dyscalculia; DD + RD = DD with reading deficit; TM = typical math; 95% BcaCI = 95% bootstrap bias-corrected and accelerated confidence interval.

was also significantly different between the children with comorbid reading and math difficulties (DD + RD) and the TM group, $\chi^2(df = 1, N = 1658) = 6.86$, $p = .008$; $\varphi = .064$; however, the frequency of children with high MA was not significantly different between the DD group and DD + RD, $\chi^2(df = 1, N = 239) = .96$, $p = .32$, $\varphi = .063$.

Figure 2B confirms that only a relatively small proportion of DD children can be categorized as having high MA independent of the DD and MA definitions used. When DD is defined as math performance below 1.5 *SD* below the mean (and reading performance within or above the average range), the percentage with high MA is 25%, which is slightly higher than the mean − 1 *SD* definition (note that this percentage is calculated out of the total number of DD children meeting the mean − 1.5 *SD* criterion: 32 children). It is important to highlight that the more conservative definition of DD depicted in Figure 2B approximates clinical diagnostic criteria for DD (mathematics performance substantially below the average performance for a child's age, with a discrepancy between mathematics performance and language abilities). However, the definition of DD did not make a notable difference to the prevalence of co-occurrence of MA and DD; thus, the remainder of our analyses refer to the original DD and high MA definitions.

It is important to note that of the students with high MA across the whole sample, only 11% fell in the DD group and 12% had below average math performance but did not meet criteria for DD (i.e., had comorbid reading difficulty). Thus, the majority of students with high MA (77%) had average or above average mathematics performance (see Table 2). The proportion of typically performing and high performing children with different MA scores is also illustrated in Figure S3 in the online supplemental materials. Table 2 also shows the median MA scores and 95% BcaCI for median MA scores.

The distributions of MA scores in the DD group by gender are shown in Figure 3. This distribution (collapsed across gender) was significantly different from normal ($n = 99$; $W = .97$; $p = .03$; skewness = .23; kurtosis = 2.47). The Mann–Whitney *U* test confirmed that the MA levels of DD girls and DD boys were different from one another ($z = -2.50$, $p = .013$; girls' $M = 24.15$, 95% BcaCI [22.12, 26.15]; boys' $M = 20.19$; 95% BcaCI [17.86, 22.78], Cohen's $d = .5$). Chi-square analysis confirmed that there were more girls with high MA (18) than boys with high MA (four) in the DD group (Fisher's exact $p = .013$). The distribution of MA scores in the DD group for each school level is shown in Figure S4 in the online supplemental materials.

Discussion

The current study aimed to investigate the association between MA and math performance, as well as the prevalence of co-occurrence of MA and DD. We also examined gender differences in DD, MA, and comorbid DD and MA. To our knowledge, we are the first to estimate the prevalence of comorbidity of DD and MA in a large representative cohort of primary and secondary school children.

We estimated the prevalence of DD using the definition used previously by Devine et al. (2013). When DD was defined as mathematics performance at least 1 *SD* below the mean and reading performance above 1 *SD* below the mean, 5.6% of the sample met the criteria for DD. This prevalence estimate is very similar to international estimates reported previously (Gross-Tsur, Manor, & Shalev, 1996; Koumoula et al., 2004). This estimate is also similar to that found in U.K. students previously using these same criteria (Devine et al., 2013).

In the whole sample, MA and mathematics performance were moderately negatively correlated ($r_s = -.30$; 95% BcaCI [−.34, −.25]), which is about the same effect size as that reported in previous meta-analyses (Hembree, 1990; Ma, 1999). The similarity between the current data and results from the 1990s is remarkable: MA seems to be a highly persistent factor in mathematical development. Due to the cross-sectional design of the

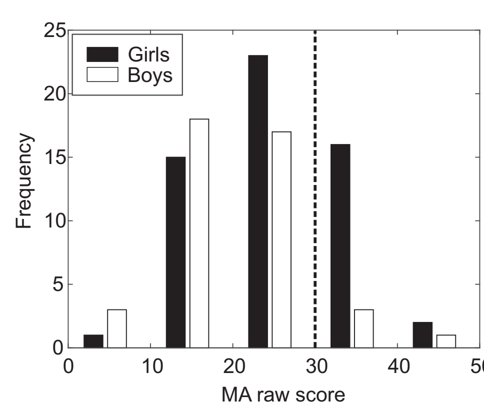

Figure 3. Distribution of mathematics anxiety (MA) scores for the developmental dyscalculia group by gender among a sample of primary and secondary school children. The high MA cutoff is shown by the dashed line.

current study, we could not determine the direction of this association. However, inspecting the prevalence of comorbidity of MA and DD allowed us to draw some conclusions about the relationship between MA and DD that add to the general literature on the MA–performance relationship.

Most notably, children with DD had as wide a range of MA levels as children in the TM group, and 78% of DD children did not have high MA. Whereas 11% of our whole sample had high MA, 22% of the DD group had high MA. Hence, high MA appears to be twice as likely in children with DD as in children with mathematics performance at or above the average range. On the one hand, this finding supports the results of previous studies that have shown higher levels of MA in children with DD or MLD (Lai et al., 2015; Passolunghi, 2011; Wu et al., 2014) and potentially lends further support to the deficit theory. However, on the other hand, of the students with high MA across the whole sample, only 11% fell in the DD group and 12% were in the DD + RD group. Thus, the majority of students with high MA (77%) had average or above average mathematics performance, demonstrating that high MA is not exclusive to children with MLD or DD.

In contrast to the idea that MA may simply equate to low math ability (Beilock & Willingham, 2014), the results of the current study suggest that many children with DD do not report high levels of MA. It is not clear why many children with DD are not highly anxious about mathematics, but it may be related to expectations or the value attached to mathematics (Eccles, 1994). That is, MA may be related to children's worries about not meeting their own or their socializers' expectations (Ho et al., 2000; Wigfield & Meece, 1988). Children with DD may not have high expectations of themselves regarding their mathematics performance (or their socializers may not have high expectations of them); therefore, some DD children may not develop anxiety toward mathematics. Similarly, mathematics may not be viewed as important by children with DD (and/or their parents or peers); thus, they may not get anxious about poor performance in the subject (Wigfield & Meece, 1988).

However, an alternative explanation could be that some children with DD may not possess the metacognitive skills necessary to accurately evaluate their mathematics abilities, and consequently, they may not perceive mathematics as anxiety inducing. Past research has revealed metacognitive deficits in MLD. More specifically, younger children with MLD are less accurate than are typically achieving children in evaluating and predicting their mathematical performance (Garrett, Mazzocco, & Baker, 2006), and adolescents with learning disabilities are more likely to overestimate their mathematics performance compared to typically achieving children (Heath, Roberts, & Toste, 2013). Therefore, it is possible that the link between MA and mathematics performance may be moderated by DD children's self-perceptions of their mathematics ability. However, children's self-perceptions were not measured in the current work, so we could not test these relationships. Yet, research has suggested that the relationship between mathematics self-ratings and performance may develop prior to the relationship between MA and performance in primary school children (Dowker, Bennett, & Smith, 2012); thus, mathematics self-ratings are important to consider. Further research is needed to investigate the link between self-perceptions of mathematics ability and MA in children with DD.

We found an equal prevalence of boys and girls with DD, which is also in line with the findings of Devine et al. (2013) and several other studies (Gross-Tsur et al., 1996; Koumoula et al., 2004; Lewis et al., 1994). However, there were more girls than boys in the DD group with comorbid MA, which is in line with the many studies that have shown that girls have higher levels of MA than do boys (reviewed in Devine et al., 2012, and Hill et al., 2016).

It is not clear why female students frequently report higher MA than do male, but several explanations have been put forward. Biological links to MA have been suggested by the study of MA in monozygotic and same-sex dizygotic twins by Wang et al. (2014), which revealed that around 40% of the variation in MA could be explained by genetic factors. Nonetheless, environmental and social factors may play crucial roles in the development of MA gender differences. For example, gender differences in socialization during childhood, particularly the introduction of gender stereotypes about mathematics, may differentially affect situational anxiety experienced by girls and boys and their mathematics performance (Bander & Betz, 1981; Fennema & Sherman, 1976). Mathematics gender stereotypes do have detrimental effects on girls' performance (Appel, Kronberger, & Aronson, 2011; Flore & Wicherts, 2015), and other work has suggested that parents' and teachers' gender-stereotyped beliefs influence children's attainment and indirectly affect children's academic choices (Eccles, 1994; Gunderson, Ramirez, Levine, & Beilock, 2012).

It is important to note that female students are also more likely to report higher levels of both TA and GA than do male (Hembree, 1988; Vesga-Lopez et al., 2008; Wren & Benson, 2004); thus, it is possible that female students' general propensity for anxiety may contribute to their higher levels of MA. However, there are other variables, such as mathematics confidence, mathematics self-concept and mathematics self-efficacy, that may contribute to the gender difference in MA; for example, several studies have shown that boys report greater confidence in mathematics and higher mathematics self-efficacy than do girls (Huang, 2013; Pajares, 2005; Wigfield, Eccles, Mac Iver, Reuman, & Midgley, 1991). Mathematics self-efficacy has been shown to be related to MA (Jain & Dowson, 2009; Meece, Wigfield, & Eccles, 1990); thus, mathematics competence beliefs may indeed contribute to MA gender differences.

We have shown that approximately one fifth of children with DD have comorbid MA, with girls being overrepresented in this group compared to boys. These findings suggest that some students, particularly girls, may be more susceptible to negative affective reactions to mathematics alongside performance deficits in the subject. Because children's mathematics performance is likely to be influenced by anxiety during assessment (Ashcraft et al., 2007; Ashcraft & Ridley, 2005), there is the possibility that highly math-anxious children may have the potential to improve their mathematics performance, if they are able to combat their MA. Indeed, research has shown that interventions that specifically address MA (rather than mathematics knowledge) have resulted in mathematics performance benefits (Hembree, 1990; Ramirez & Beilock, 2011). For example, Hembree (1990) reported that interventions that focused on systematic desensitization or cognitive restructuring resulted in improvements in mathematics performance. More recently, Ramirez and Beilock (2011) also found performance benefits when participants wrote about their anxieties before an examination. The authors theorized that writing about one's anxieties before a test reduces the need to worry during the test, which decreases rumination and frees up working memory resources, thereby improving test performance. Collectively, these results suggest that test performance can indeed be improved via the alleviation of MA and/or TA; thus, some of the DD children with comorbid high MA may be able to improve their performance by overcoming or reducing MA, to the point that they may no longer meet DD inclusion criteria. Therefore, we believe that identifying MA in the classroom is essential so that children can be equipped with appropriate coping strategies for dealing with anxious reactions toward mathematics, particularly around assessment.

Our findings challenge the suggestion that deficits in basic numerical processing underlie MA (Maloney et al., 2010, 2011), because here we show that although there is some degree of overlap between them, MA and numerical deficits (characteristic of DD) are dissociable. Our results suggest that cognitive deficits (DD) mostly exist in the absence of emotional problems (MA) and vice versa and likely require quite different types of interventions. Children affected by MA, or co-occurring MA and DD, are likely to benefit from the types of interventions we have outlined, rather than interventions focusing on the improvement of mathematical skills. Indeed, Hembree's (1990) meta-analysis of MA studies revealed that interventions for MA that focus on the cognitive aspects of anxiety were more effective than were interventions that attempted to reduce MA through mathematics tuition or curricular changes. Moreover, the previously mentioned interventions that focused on relieving the cognitive symptoms of anxiety, particularly those that are purported to free up working memory resources, have shown promising results for the relief of anxiety and the improvement of performance (Hembree, 1990; Ramirez & Beilock, 2011). On the other hand, children with DD who do not have negative emotional reactions toward mathematics are likely to benefit from interventions that target the development of mathematical skills, working memory, and visuospatial processing (J. Holmes, Gathercole, & Dunning, 2009; W. Holmes & Dowker, 2013; Lambert & Spinath, 2014; Wißmann, Heine, Handl, & Jacobs, 2013). Nonetheless, children with DD are also likely to benefit from the encouragement of positive attitudes toward mathematics, which may, for example, foster engagement with mathematics, encourage persistence despite difficulty with the subject, and mitigate the development of anxiety toward mathematics in the future. Indeed, longitudinal research has suggested that characteristics such as conscientiousness, self-control, grit (i.e., persistence toward long-term goals; Duckworth, Peterson, Matthews, & Kelly, 2007) and growth mind set (i.e., the belief that academic ability can be improved with effort; Dweck, 2006) are associated with mathematics performance gains during middle school (West et al., 2016).

Although it is likely that MA is triggered by past poor performance in some cases (e.g., potentially in children with DD and high MA), our results suggest that the deficit theory may explain the MA–performance relationship in only a small proportion of children. Furthermore, our research shows that a much greater proportion of children with high MA have typical mathematical performance. This is also apparent in the observation that the most conspicuous feature of the correlation between MA and mathematics performance seems to be a drop in the number of mathematically high-achieving children with increasing MA levels rather than an increase in the number of very poor achievers (note the lack of observations in the upper right triangular section of Figure 2A). Our findings suggest that many children who are performing adequately in math may in fact be struggling with MA. These children may "slip under the radar" if teachers and parents–caregivers rely on mathematics achievement as a measure of children's mathematical well-being. Competent mathematicians with high MA still run the risk of developing further negative attitudes toward mathematics, potentially leading to avoiding mathematics and dropping out of elective mathematics classes in the future (Ashcraft, 2002; Hembree, 1990; Ma, 1999). Collectively, the MA literature has suggested that the MA–performance association may function reciprocally or as a vicious circle (Carey et al., 2016). Thus, even if students with high MA are performing within the average range at one time point, MA may lead to poorer educational outcomes in the future, probably mainly because of the avoidance of higher level elective mathematics classes. Our findings therefore emphasize the importance of identifying MA in children of all ability levels, and we suggest that attendance to children's affective reactions during mathematics learning should be considered an essential element of educational provision.

Taken together, our results suggest that cognitive and emotional mathematics problems largely dissociate and call into question the idea that MA is exclusively linked to poor mathematics ability. Different intervention methods need to be developed to prevent and treat emotional and cognitive blocks of mathematical development.

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Appendix

mAMAS

A modified version of the Abbreviated Math Anxiety Scale (Hopko, Mahadevan, Bare, & Hunt, 2003).

Instructions:

Please give each sentence a score in terms of how anxious you would feel during each situation. Use the scale at the right side and circle the number which you think best describes how you feel.

Item	☺ Low anxiety	Some anxiety	Moderate anxiety	Quite a bit of anxiety	☹ High anxiety
1. Having to complete a worksheet by yourself.	1	2	3	4	5
2. Thinking about a maths test the day before you take it.	1	2	3	4	5
3. Watching the teacher work out a maths problem on the board.	1	2	3	4	5
4. Taking a maths test.	1	2	3	4	5
5. Being given maths homework with lots of difficult questions that you have to hand in the next day.	1	2	3	4	5
6. Listening to the teacher talk for a long time in maths.	1	2	3	4	5
7. Listening to another child in your class explain a maths problem.	1	2	3	4	5
8. Finding out you are going to have a surprise maths quiz when you start your maths lesson.	1	2	3	4	5
9. Starting a new topic in maths.	1	2	3	4	5

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