MATHEMATICAL AND STATISTICS ANXIETY: EDUCATIONAL, SOCIAL, DEVELOPMENTAL AND COGNITIVE PERSPECTIVES

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PUBLISHED IN: Frontiers in Psychology

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88945-076-3
DOI 10.3389/978-2-88945-076-3

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MATHEMATICAL AND STATISTICS ANXIETY: EDUCATIONAL, SOCIAL, DEVELOPMENTAL AND COGNITIVE PERSPECTIVES

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Cover image by Dr Bianca van Bers.

Mathematical anxiety is a feeling of tension, apprehension or fear which arises when a person is faced with mathematical content. The negative consequences of mathematical anxiety are well-documented. Students with high levels of mathematical anxiety might underperform in important test situations, they tend to hold negative attitudes towards mathematics, and they are likely to opt out of elective mathematics courses, which also affects their career opportunities. Although at the university level many students do not continue to study mathematics, social science students are confronted with the fact that their disciplines involve learning about statistics - another potential source of anxiety for students who are uncomfortable with dealing with numerical content.

Research on mathematical anxiety is a truly interdisciplinary field with contributions from educational, developmental, cognitive, social and neuroscience researchers. The current collection of papers demonstrates the diversity of the field, offering both new empirical contributions and reviews of existing studies. The contributors also outline future directions for this line of research.

Citation: Morsanyi, K., Mammarella, I. C., Szűcs, D., Tomasetto, C., Primi, C., Maloney, E. A., eds. (2017). Mathematical and Statistics Anxiety: Educational, Social, Developmental and Cognitive Perspectives. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-076-3

Table of Contents

frontiers in Psychology

EDITORIAL
published: 21 July 2016
doi: 10.3389/fpsyg.2016.01083

Editorial: Mathematical and Statistics Anxiety: Educational, Social, Developmental and Cognitive Perspectives

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Keywords: anxiety specificity, developmental change, emotional factors, gender differences, mathematical anxiety, mathematics performance, measurement

The Editorial on the Research Topic

Mathematical and Statistics Anxiety: Educational, Social, Developmental and Cognitive Perspectives

OPEN ACCESS

Edited and reviewed by:
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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *23 June 2016*
Accepted: *01 July 2016*
Published: *21 July 2016*

Citation:
Morsanyi K, Mammarella IC, Szücs D, Tomasetto C, Primi C and Maloney EA (2016) Editorial: Mathematical and Statistics Anxiety: Educational, Social, Developmental and Cognitive Perspectives. Front. Psychol. 7:1083. doi: 10.3389/fpsyg.2016.01083

Mathematical anxiety (MA) is a feeling of apprehension and fear related to mathematics (e.g., Ashcraft, 2002). High levels of MA have serious implications for a person's life prospects, as they can lead to an avoidance of elective maths courses, which, in turn, affects people's career opportunities (e.g., Hembree, 1990). The societal importance of MA is also underlined by the fact that, according to the latest report of the Organization for Economic Co-operation and Development, on average 30.6% of adolescents get very nervous when they have to do maths problems (OECD, 2015).

Research in this area has shown an exponential growth in recent years, with the number of papers dealing with MA increasing from 60 in the year 2000 to 330 papers published in 2015 (based on Scopus statistics accessed on 20/06/2016). Over half of these papers have reported research carried out in North America, mostly in the United States, whereas less than 20% of this work was conducted in Europe. The majority of these papers appeared in educational journals, with a smaller proportion published in cognitive or developmental journals, and even fewer in neuroscience journals or in specialist journals on emotion or stress.

Against this backdrop, it is easier to see the contribution of this collection of papers to the literature. Most of the contributors are from European countries, and many papers deal with relatively less-investigated issues, including the relationship between MA and social influences, the measurement of MA, the physiological correlates of MA, and MA outside the classroom. The Topic also includes a number of review papers that, besides summarizing existing findings, highlight some important gaps in our current knowledge and make recommendations for future investigations. Finally, some papers present methodological innovations.

MA RESEARCH: THE FIRST 60 YEARS AND BEYOND

Dowker et al. summarize many of the most important MA-related findings since the first publication on the topic almost 60 years ago. Dowker et al. discuss the separability of MA from other related constructs (e.g., general- and test-anxiety, and attitudes to mathematics), as well as some issues regarding the measurement of MA. Dowker et al. also explore some other correlates of MA (e.g., physiological and socio-cultural processes), and tentative approaches to reduce or prevent MA. Finally, the paper also points to directions for future research, some of which (e.g., the relationship between gender stereotypes and MA, and the "chicken or egg" question of the link between MA and mathematics performance) were in the focus of other contributions.

MA AND BASIC PROCESSING OF NUMBERS

Another review paper by Artemenko et al. provides an overview of the neural correlates of MA. Artemenko et al. argue that whereas behavioral studies mostly observe an influence of MA on difficult maths tasks, neurophysiological studies show that processing efficiency is also affected in basic number processing. This conclusion is in line with Dietrich et al. who replicated previous findings by Maloney et al. (2011) and Núñez-Peña and Suárez-Pellicioni (2014) by showing a larger symbolic distance effect in maths anxious individuals. At the same time, Dietrich et al. question earlier conclusions that maths anxious individuals have a deficient approximate number system.

MA, ATTENTIONAL RESOURCES, WORKING MEMORY, AND INHIBITION

Artemenko et al. also discuss the neurological evidence supporting Eysenck et al.'s (2007) attentional control theory. According to this theory, attentional, and processing resources are impaired by worry, and this can only be compensated by increased cognitive effort. Four contributions within the Topic address related issues. Both Rubinsten et al. and Suárez-Pellicioni et al. present behavioral evidence for an attentional bias in MA toward threatening (i.e., maths-related) stimuli. These authors argue that this bias could lead to the exacerbation of MA, as it could result in an overestimation of the level of threat in maths-related situations. In another contribution, Núñez-Peña and Suárez-Pellicioni also present evidence from event-related potentials for attentional and processing differences between high- and low-MA individuals, while they perform multi-digit additions.

Passolunghi et al. compare the academic achievement and cognitive profiles of secondary school students with high and low MA. Passolunghi et al. show that, besides lower achievement in mathematics, students with high MA perform less well in verbal short-term memory and working memory tasks, and are less able to inhibit irrelevant information. Additionally, measures of inhibitory control and fact retrieval were the best predictors for identifying students with high or low MA. A notable methodological feature of the studies by Núñez-Peña and Suárez-Pellicioni, Passolunghi et al., and Suárez-Pellicioni et al. is that they recruited participants with particularly high/low levels of MA, and compared these extreme groups.

THE RELATIONSHIP BETWEEN MA AND MATHS PERFORMANCE

Whereas it is well-established that there is a moderate negative relationship between MA and maths performance (see Hembree, 1990 and Ma, 1999 for meta-analyses), the evidence regarding the direction of a possible causal link is mixed. In the previous sections we described evidence for the potential of MA to disrupt mathematical performance, and even very basic maths-related processing. Besides evidence for this Debilitating Anxiety Model, Carey et al. also review the findings supporting the Deficit Theory (i.e., that poor maths performance might elicit MA; cf., Tobias, 1986). Carey et al. propose that instead of trying to decide between these proposals, a Reciprocal Theory (where the causal link between MA and maths performance is bidirectional) seems most plausible. Nevertheless, they also point to the scarcity of longitudinal research that could provide further evidence for the Deficit Theory.

The only paper in the Topic dealing with Statistics Anxiety (SA; Macher et al.) also discusses the link between anxiety and performance. Macher et al. propose that although during examinations SA might disrupt performance, SA could be related to greater motivation to avoid failure, and, thus, could be positively linked to the effort invested into exam preparation. In other words, SA can both support and hinder performance, although these effects might arise at different points in time. The question of expectations about maths performance prior to testing is further addressed by Erickson and Heit.

IDENTIFICATION WITH MATHS, MATHS CONFIDENCE, AND MA

Erickson and Heit investigate the link between self-confidence and actual performance in maths, biology and literature in university undergraduates. Erikson and Heit compare students' performance estimates before and after a test in each subject. Students generally overestimated their performance when they made predictions before completing the tests, but this tendency was strongest in the case of maths. This overconfidence in maths is interesting, given that Study 2 demonstrated high levels of MA in participants. Erikson and Heit point out that both MA and overconfidence could lead to avoidance behaviors, such as spending less time on exam preparation or missing classes.

Necka et al. introduce a single-item measure of self-maths overlap, modeled on Aron et al.'s (1992) the Inclusion of Other in Self Scale. Necka et al. demonstrate that self-maths overlap is negatively related to MA. Moreover, MA is more strongly related to maths performance in individuals with low self-maths overlap (i.e., in individuals who perceive maths as less self-relevant). Notably, this difference appears to be only partially explained by the tendency of individuals with high self-maths overlap to overestimate their maths ability.

Jansen et al. present a new scale to measure the tendency to use maths in everyday life, and they also investigate its relationship with maths skills, perceived maths competence and MA in a large adult sample. Jansen et al. report gender differences in all of these constructs, showing a male advantage. In both genders, perceived maths competence mediated the link between maths skills and everyday use of maths. In women only, MA was an additional mediator of the link between maths skills and everyday use of maths. This study adds to the limited literature on gender differences in the link between MA and maths performance (e.g., Devine et al., 2012; Hill et al., 2016).

SOCIAL INFLUENCES, GENDER STEREOTYPES, AND MA

The relationship between the development of MA and social influences, such as parents' endorsement of maths-related gender stereotypes (e.g., Tomasetto et al., 2015) is a relatively neglected issue within the MA literature. Two contributions to the Topic have investigated parental influences. Casad et al. demonstrate that parents' MA interacts with their child's MA to predict the child's self-efficacy, classroom maths performance, and maths-related attitudes.

Bosman and De Smedt further argue that MA might reflect a maladaptive affect-regulation mechanism that is characteristic of insecure attachment relationships. Their hypothesis was supported by the finding that individual differences in MA were related to insecure attachment, independent of age, sex, and IQ. Additionally, mathematics achievement was associated with insecure attachment and this effect was mediated by MA.

Bieg et al. extend previous work by Goetz et al. (2013) that showed higher trait MA in females, but no gender difference in state MA. Bieg et al. demonstrate that the discrepancy between state and trait MA (i.e., the tendency to overestimate MA) was stronger in females who endorsed the gender stereotype of maths being a male domain.

MEASUREMENT OF MA AND CROSS-CULTURAL VALIDITY OF MEASUREMENT SCALES

As most MA scales have been developed in North America, it is important to establish the cross-cultural validity of these instruments. Cipora et al. investigate the psychometric properties of the Polish adaptation of the Abbreviated Math Anxiety Scale (AMAS; Hopko et al., 2003), a widely used 9-item scale. Cipora et al. demonstrate high reliability, as well as very good construct, convergent and discriminant validity. This adds to previous work that demonstrated the excellent psychometric properties of the Iranian (Vahedi and Farrokhi, 2011) and Italian (Primi et al., 2014) adaptations of the AMAS.

Pletzer et al. present the psychometric analysis of a German adaptation of the MARS30-brief (Suinn and Winston, 2003), and propose that a five-factor model (including Evaluation Anxiety, Learning Mathematics Anxiety, Everyday Numerical Anxiety, Performance Anxiety, and Social Responsibility Anxiety) is the best fitting and most parsimonious representation of the factorial structure of the scale. They also establish the measurement invariance of the scale across genders, and show that gender differences are specific to Evaluation Anxiety, Learning Mathematics Anxiety, and Performance Anxiety.

CONCLUSIONS AND LOOKING AHEAD TO THE NEXT 60 YEARS

Extending contributions from North American researchers, the present collection of papers brings European research into MA to the forefront, while exploring some novel and less-researched issues, such as MA and basic numerical processing; the social determinants of MA; and the links between MA, self-concept, and self-confidence.

This Topic also offers some methodological innovations, including comparisons between extreme groups of high- and low-MA participants, and new measures of self-maths overlap, as well as using maths in everyday life. Investigating MA in everyday situations could be an important direction for future research, as recent studies indicate that the effect of MA extends beyond educational contexts. Specifically, MA has been found to be linked to decision-making skills (Morsanyi et al., 2014; Silk and Parrott, 2014).

Nevertheless, there are also some topics that remained partially or wholly unaddressed by these contributions. Although the origins of MA are not well-understood, research into MA with young children remains scarce (although see e.g., Berkowitz et al., 2015; Maloney et al., 2015; Ramirez et al., 2016). Longitudinal studies with young children (e.g., Cargnelutti et al., 2016) would be particularly important for a better understanding of the origins of MA.

Further investigations into the measurement of MA are also necessary. Researchers use various instruments (ranging from single-item scales to instruments that consist of 30 or more items). The psychometric properties of these scales might differ considerably, and this can result in inconsistencies between the findings of studies. It is also common that studies with young participants use scales developed for adults, or instruments that were developed to measure MA in educational contexts are administered to adults who are no longer in education. Rolison et al. (2016) presented a scale to measure MA outside academic contexts. Investigations into MA in everyday life could make it possible to extend this work to new populations (e.g., older adults) and new contexts, such as decisions about investments, consumer behavior or lifestyle choices.

AUTHOR CONTRIBUTIONS

All authors listed have made substantial, direct, and intellectual contribution to the work, and approved it for publication.

FUNDING

The writing of this paper was supported by a Royal Society International Exchanges grant to KM and CT (reference number: IE150463).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

REVIEW
published: 25 April 2016
doi: 10.3389/fpsyg.2016.00508

Mathematics Anxiety: What Have We Learned in 60 Years?

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The construct of mathematics anxiety has been an important topic of study at least since the concept of "number anxiety" was introduced by Dreger and Aiken (1957), and has received increasing attention in recent years. This paper focuses on what research has revealed about mathematics anxiety in the last 60 years, and what still remains to be learned. We discuss what mathematics anxiety is; how distinct it is from other forms of anxiety; and how it relates to attitudes to mathematics. We discuss the relationships between mathematics anxiety and mathematics performance. We describe ways in which mathematics anxiety is measured, both by questionnaires, and by physiological measures. We discuss some possible factors in mathematics anxiety, including genetics, gender, age, and culture. Finally, we describe some research on treatment. We conclude with a brief discussion of what still needs to be learned.

Keywords: mathematics anxiety, working memory, gender, stereotype threat, cognitive reappraisal, transcranial direct current stimulation (tDCS)

OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *06 August 2015*
Accepted: *24 March 2016*
Published: *25 April 2016*

Citation:
Dowker A, Sarkar A and Looi CY (2016) Mathematics Anxiety: What Have We Learned in 60 Years? Front. Psychol. 7:508. doi: 10.3389/fpsyg.2016.00508

Low achievement and low participation in mathematics are matters of concern in many countries; for example, recent concerns in the UK led to the establishment of the National Numeracy organization in 2012. This topic has received increasing focus in recent years, the ever-increasing importance of quantitative reasoning in a variety of educational and occupational situations, ranging from school examinations to management of personal finances.

Some aspects of mathematics appear to be cognitively difficult for many people to acquire; and some people have moderate or severe specific mathematical learning disabilities. But not all mathematical disabilities result from cognitive difficulties. A substantial number of children and adults have mathematics anxiety, which may severely disrupt their mathematical learning and performance, both by causing avoidance of mathematical activities and by overloading and disrupting working memory during mathematical tasks. On the whole, studies suggest that attitudes to mathematics tend to deteriorate with age during childhood and adolescence (Wigfield and Meece, 1988; Ma and Kishor, 1997), which has negative implications for mathematical development, mathematics education and adult engagement in mathematics-related activities. Also, while there are nowadays few gender differences in actual mathematical performance in countries that provide equal educational opportunity for boys and girls, females at all ages still tend to rate themselves lower in mathematics and to experience greater anxiety about mathematics than do males. It is important to understand children's and adults' attitudes and emotions with regard to mathematics if we are to remove important barriers to learning and progress in this subject.

Many studies over the years have indicated that many people have extremely negative attitudes to mathematics, sometimes amounting to severe anxiety (Hembree, 1990; Ashcraft, 2002; Maloney and Beilock, 2012). Mathematics anxiety has been 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 and Suinn, 1972).

Although, many studies treat mathematics anxiety as a single entity, it appears to consist of more than one component. Wigfield and Meece (1988) found two separate dimensions of mathematics anxiety in sixth graders and secondary school students and found two different dimensions: cognitive and affective, similar to those that had been previously identified in the area of test anxiety by Liebert and Morris (1967). The cognitive dimension, labeled as "worry," refers to concern about one's performance and the consequences of failure, and the affective dimension, labeled as "emotionality" refers to nervousness and tension in testing situations and respective autonomic reactions (Liebert and Morris, 1967).

People have been expressing mathematics anxiety for centuries: the verse "Multiplication is vexation ... and practice drives me mad" goes back at least to the sixteenth century. From a research perspective, the construct has been an important topic of study at least since the concept of "number anxiety" was introduced by Dreger and Aiken (1957), and has received increasing attention in recent years, in conjunction with the generally increased focus on mathematical performance.

Although, as will be discussed below, it is unclear to what extent mathematics anxiety causes mathematical difficulties, and to what extent mathematical difficulties and resulting experiences of failure cause mathematics anxiety; there is significant evidence that mathematics anxiety interferes with performance of mathematical tasks, especially those that require working memory. Moreover, whether a person likes or fears mathematics will clearly influence whether they take courses in mathematics beyond compulsory school-leaving age, and pursue careers that require mathematical knowledge (Chipman et al., 1992; Brown et al., 2008). Thus, mathematics anxiety is of great importance to the development and use of mathematical skills. It is also important in itself, as a cause of much stress and distress.

This paper will focus on what research has revealed about mathematics anxiety in the last 60 years, and what still remains to be learned. We will discuss what mathematics anxiety is, and how distinct it is from other forms of anxiety. We will discuss its relationship to attitudes to mathematics. We will then discuss the relationships between mathematics anxiety and mathematics performance and possible reasons for them. We will then discuss ways in which mathematics anxiety is measured, both by the commonest technique of questionnaires, and by physiological measures. We will then discuss some possible factors in mathematics anxiety, including genetics, gender, age, and culture. Finally and importantly, we will discuss some implications for treatment. We will conclude with a brief discussion of what still needs to be learned.

IS MATHEMATICS ANXIETY SEPARABLE FROM OTHER FORMS OF ANXIETY?

Though, as will be discussed below, mathematics anxiety is closely related to mathematical performance, it cannot be reduced just to a problem with mathematics. It seems to be as much an aspect of "anxiety" as an aspect of "mathematics." Indeed, before assuming that mathematics anxiety is an entity in its own right, it is necessary to consider relationships between mathematics anxiety and other forms of anxiety, especially test anxiety, and general anxiety. Several studies suggest that mathematics anxiety is more closely related to other measures of anxiety, especially test anxiety, than to measures of academic ability and performance (Hembree, 1990; Ashcraft et al., 1998). Such studies typically show correlations of 0.3 and 0.5 between measures of mathematics anxiety and test anxiety.

Mathematics anxiety has also generally been found to correlate with measures of general anxiety; and it is indeed possible that this may serve as a background variable explaining some of the correlation between mathematics anxiety and test anxiety. For example, Hembree (1990) found a mean correlation of 0.35 between the MARS and a measure of general anxiety. In a behavioral genetic study, to be discussed in more detail below, Wang et al. (2014) obtained evidence that genetically based differences in general anxiety contribute to genetic differences in mathematics anxiety.

However, mathematics anxiety cannot be reduced to either test anxiety or general anxiety. Different measures of mathematics anxiety correlate more highly with one another (0.5–0.8) than with test anxiety or general anxiety (Dew et al., 1983; Hembree, 1990; review by Ashcraft and Ridley, 2005).

People may exhibit performance anxiety not only about tests and examinations, but about a variety of school subjects. Mathematics is usually assumed to elicit stronger emotional reactions, and especially anxiety, than most other academic subjects, but this assumption needs more research (Punaro and Reeve, 2012). Although, the general assumption is that people show much more anxiety and other negative attitudes toward mathematics than other academic subjects, there have not been many studies directly comparing attitudes to mathematics and other subjects.

Certainly anxiety toward other subjects exists, especially when performance in these subjects takes place in front of others. People with dyslexia have been found to exhibit anxiety about literacy (Carroll et al., 2005; Carroll and Iles, 2006). It is well-known, that foreign language learning and use, especially by adults, is often inhibited by anxiety (Horwitz et al., 1986; Cheng et al., 1999; Wu and Lin, 2014). Music students, and even successful musicians, often demonstrate music performance anxiety (Kenny, 2011).

Drawing also elicits performance anxiety and lack of confidence, and there is a decline in confidence with age, which in some ways parallels findings with regard to mathematics. Most young children enjoy drawing, and will often draw spontaneously. Many authors report that interest in drawing seems to decline in most children at or before the transition to secondary school, and many older children and adults will insist that they "can't draw," even though they had drawn frequently and enthusiastically some years earlier (Cox, 1989; Thomas and Silk, 1990; Golomb, 2002; but see Burkitt et al., 2010 for somewhat conflicting findings).

Punaro and Reeve (2012) reported a study that directly compared mathematics and literacy anxiety in Australian 9-year-olds and related their anxiety to their actual academic abilities. Although, children expressed anxiety about difficult problems in both mathematics and literacy, worries were indeed greater for mathematics than literacy. Moreover, anxiety about mathematics was related to actual mathematics performance, whereas anxiety about literacy was not related to actual literacy performance. This study would suggest that although mathematics is not the only subject that elicits anxiety, anxiety may indeed be more severe, and possibly affect performance more, for mathematics than for other subjects.

MATHEMATICS ANXIETY AND ATTITUDES TO MATHEMATICS

Attitudes to mathematics, even negative attitudes, cannot be equated with mathematics anxiety, as the former are based on motivational and cognitive factors, while anxiety is a specifically emotional factor. Nevertheless, attitude measures tend to correlate quite closely with mathematics anxiety. For example, Hembree (1990) found that in school pupils, mathematics anxiety showed a mean correlation of −0.73 with enjoyment of mathematics and −0.82 with confidence in mathematics. In college students, the equivalent mean correlations were a little lower than in schoolchildren, but still very high: −0.47 between mathematics anxiety and enjoyment of mathematics, and −0.65 between mathematics anxiety and confidence in mathematics.

Mathematics anxiety seems to be particularly related to self-rating with regard to mathematics. People who think that they are bad at mathematics are more likely to be anxious. Most studies indicate a negative relationship between mathematics self-concept and mathematics anxiety (Hembree, 1990; Pajares and Miller, 1994; Jain and Dowson, 2009; Goetz et al., 2010; Hoffman, 2010).

However, as most of these studies are correlational rather than longitudinal, it is hard once again to establish the direction of causation: does anxiety lead to a lack of confidence in one's own mathematical ability, or does a lack of confidence in one's mathematical ability make one more anxious? Ahmed et al. (2012) carried out a longitudinal study of 495 seventh-grade pupils, who completed self-report measures of both anxiety and self-concept three times over a school year. Structural equation modeling suggested that each characteristic influenced the other over time, but that the effect of self-concept on subsequent anxiety was significantly greater than the effect of anxiety on subsequent self-concept. The details of the results should be taken with some caution, because although the study was longitudinal, it was over a relatively short period (one school year) and also a different pattern might be seen among younger or older children. However, it provides evidence that the relationship between mathematics anxiety and mathematics self-concept is reciprocal: each influences the other.

A closely related construct is self-efficacy. Ashcraft and Rudig (2012) adapted Bandura's (1977) definition of self-efficacy to the topic of mathematics, stating that "self-efficacy is an individual's confidence in his or her ability to perform mathematics and is thought to directly impact the choice to engage in, expend effort on, and persist in pursuing mathematics" (p. 249). It is not precisely the same construct as self-rating, as it includes beliefs about the ability to improve in mathematics, and to take control of one's learning, rather than just about one's current performance; but there is of course significant overlap between the constructs. Studies have demonstrated an inverse relationship between self-efficacy and math anxiety (Cooper and Robinson, 1991; Lee, 2009).

Attitudes to mathematics also involve conceptualization of what mathematics is, and it is possible that this is relevant to mathematics anxiety. Many people seem to regard mathematics only as school-taught arithmetic, and may not consider other cultural practices involving numbers as mathematics (Harris, 1997). Also, people may not recognize that arithmetical ability (even without considering other aspects of mathematics) is made up of many components, not just a single unitary ability (Dowker, 2005). This can risk their assumption that if they have difficulty with one component, they must be globally "bad at maths," thus increasing the risk of mathematics anxiety.

Most studies of mathematics anxiety have not differentiated between different components of mathematics, and it is likely that some components would elicit more anxiety than others and that the correlations between anxiety about different components might not always be very high. Indeed, studies which have looked separately at statistics anxiety and (general) mathematics anxiety in undergraduates have suggested that the two should be seen as separate constructs, and differ in important ways. For example, as will be discussed in the Section Gender and Mathematics Anxiety, most studies suggest that females show more mathematics anxiety than males, but there are no gender differences in statistics anxiety (Baloğlu, 2004).

PREVALENCE OF MATHEMATICS ANXIETY

Estimates of the prevalence of mathematics anxiety vary quite widely, and are of course likely to be dependent on the populations being sampled, on the measures used (though many of the studies involve similar measures), and, perhaps especially, on what criteria are used to categorize people as "mathematics anxious." Most measures of mathematics anxiety assess scores on continuous measures, and there is no clear criterion for how severe the anxiety must be for individuals to be labeled as high in mathematics anxiety.

Richardson and Suinn (1972) estimate that 11% of university students show high enough levels of mathematics anxiety to be in need of counseling. Betz (1978) concluded that about 68% of students enrolled in mathematics classes experience high mathematics anxiety. Ashcraft and Moore (2009) estimated that 17% of the population have high levels of mathematics anxiety. Johnston-Wilder et al. (2014) found that about 30% of a group of apprentices showed high mathematics anxiety, with a further 18% affected to a lesser degree. Chinn (2009) suggested the far lower figure of 2–6% of secondary school pupils in England, which may simply indicate the use of an unusually strict criterion for defining pupils as having high mathematics anxiety. There is no doubt, even when taking the lowest estimates, that it is a very significant problem.

RELATIONSHIPS BETWEEN MATHEMATICS ANXIETY AND MATHEMATICS PERFORMANCE

Numerous studies have shown that emotional factors may play a large part in mathematical performance, with mathematics anxiety playing a particularly large role (McLeod, 1992; Ma and Kishor, 1997; Ho et al., 2000; Miller and Bichsel, 2004; Baloğlu and Koçak, 2006). Mathematics anxiety scores correlate negatively with scores on tests of mathematical aptitude and achievement, while usually showing no significant correlation with verbal aptitude and achievement.

One possible reason for the negative association between mathematics anxiety and actual performance is that people who have higher levels of math anxiety are more likely to avoid activities and situations that involve mathematics. Thus, they have less practice (Ashcraft, 2002), which is in itself likely to reduce their fluency and their future mathematical learning.

Mathematics anxiety might also influence performance more directly, by overloading working memory (Ashcraft et al., 1998). Anxious people are likely to have intrusive thoughts about how badly they are doing, which may distract attention from the task or problem at hand and overload working memory resources. It has been found in many studies over the years that general anxiety as a trait is associated with working memory deficits (Mandler and Sarason, 1952; Eysenck and Calvo, 1992; Fox, 1992; Berggren and Derakhshan, 2013). It would appear likely that if anxiety affects working memory, it would have a particularly strong effect on arithmetic, as working memory has been found in many studies to be strongly associated with arithmetical performance, especially in tasks that involve multi-digit arithmetic and/or involve carrying (e.g., Hitch, 1978; Fuerst and Hitch, 2000; Gathercole and Pickering, 2000; Swanson and Sachse-Lee, 2001; Caviola et al., 2012). Thus, the load that mathematics anxiety and associated ruminations place on working memory could be a plausible explanation for decrements in mathematical performance.

Ashcraft and Kirk (2001) found that people with high maths anxiety demonstrated smaller working memory spans than people with less maths anxiety, especially in tasks that required calculation. In particular, they were much slower and made many more errors than others in tasks where they had to do mental addition at the same time as keeping numbers in memory.

DeCaro et al. (2010) asked adult participants to work out verbally based and spatially based mathematics problems in either low-pressure or high-pressure testing situations. Performance on problems that relied heavily on verbal WM resources was less accurate under high-pressure than under low-pressure tests. Performance on spatially based problems that do not rely heavily on verbal WM was not affected by pressure. Asking some individuals to focus on the problem steps by talking aloud helped to reduce pressure-induced worries and eliminated pressure's negative impact on performance.

While Ashcraft's theory emphasizes the ways in which mathematics anxiety impairs mathematical performance, some researchers such as Núñez-Peña and Suárez-Pellicioni (2014) put more emphasis on how pre-existing mathematical difficulties might cause or increase mathematics anxiety. Poor mathematical attainment may lead to mathematics anxiety, as a result of repeated experiences of failure.

Indeed, it appears that mathematics anxiety is associated not only with performance in high-level calculation skills that require the use of working memory resources, but also with much more basic numerical skills. For example, Maloney et al. (2011) gave high mathematics-anxious (HMA) and low mathematics-anxious (LMA) individuals two variants of the symbolic numerical comparison task. In two experiments, a numerical distance by mathematics anxiety (MA) interaction was obtained, demonstrating that the effect of numerical distance on response times was larger for HMA than for LMA individuals. The authors suggest that HMA individuals have less precise representations of numerical magnitude than their LMA peers; and that this may be primary, and precede the mathematics anxiety. In other words, mathematics anxiety may be associated with low-level numerical deficits that compromise the development of higher-level mathematical skills. Núñez-Peña and Suárez-Pellicioni (2014) also found that people with HMA showed a larger distance effect as well as a larger size effect (longer reaction times to comparisons involving larger numbers) than LMA individuals. Maloney and Beilock (2012) proposed that mathematics anxiety is likely to be due *both* to pre-existing difficulties in mathematical cognition *and* to social factors, e.g., exposure to teachers who themselves suffer from mathematics anxiety. Additionally, they proposed that those with initial mathematical difficulties are also likely to be more vulnerable to the negative social influences; and that this may create a vicious circle.

Studies of the relationship between mathematics anxiety and performance also need to take into account that, as stated at the beginning of this paper, mathematics anxiety consists of different components, often termed "cognitive" and "affective." The cognitive and affective dimensions seem to be differently related to achievement in mathematics. For example, in sixth graders and secondary school students, the affective dimension of math anxiety has found to be more strongly negatively correlated with achievement than the cognitive dimension (Wigfield and Meece, 1988; Ho et al., 2000). It also needs to be remembered that, even before considering the non-numerical aspects of mathematics, arithmetic itself is not a single entity, but is made up of many components (Dowker, 2005).

ASSESSMENTS OF MATHEMATICS ANXIETY

So far, we have been discussing mathematics anxiety without much reference to the methods used for studying it. However, in order to study mathematics anxiety, it is necessary to find suitable ways of assessing and measuring it. Most measures for assessing mathematics anxiety involve questionnaires and rating scales, and are predominantly used with adolescents and adults. The first such questionnaire to our knowledge is that of Dreger and Aiken (1957); and subsequent well-known examples include the Mathematics Anxiety Research Scale or MARS (Richardson and Suinn, 1972) and the Fennema–Sherman Mathematics Attitude Scales (Fennema and Sherman, 1976).

Some questionnaires, mainly including pictorial rating scales, have since been developed for use with primary school children; e.g., the Mathematics Attitude and Anxiety Questionnaire (Thomas and Dowker, 2000; Krinzinger et al., 2007; Dowker et al., 2012) and the Children's Attitude to Math Scale (James, 2013).

The reliability of mathematics anxiety questionnaires has generally been found to be good, whether measured through inter-rater reliability, test-retest reliability or internal consistency. The test whose psychometric properties have been most frequently assessed is the MARS, in its original form and in various adaptations, and it has been consistently found to be highly reliable (e.g., Plake and Parker, 1982; Suinn et al., 1972; Levitt and Hutton, 1984; Suinn and Winston, 2003; Hopko, 2003).

Good reliability has also been found for other mathematics anxiety measures such as Betz's (1978) Mathematics Anxiety Scale (Dew et al., 1984; Pajares and Urban, 1996) and the Fennema–Sherman scales (Mulhern and Rae, 1998). The mathematics anxiety scales developed specifically for children have also been found to have good reliability, including Thomas and Dowker's (2000) Mathematics Anxiety Questionnaire (Krinzinger et al., 2007); James' (2013) Children's Anxiety in Math Scale; and the scale developed by Vukovic et al. (2013).

Thus, it is unlikely that any ambiguous or conflicting results in different studies are likely to be due to unreliability of the measures. However, there are potential problems with questionnaire measures as such. In particular, a potential problem with questionnaire measures is that, like all self-report measures, they may be influenced both by the accuracy of respondents' self-perceptions and by their truthfulness in reporting. There are some studies that have attempted to combat this problem by using physiological measures of anxiety when exposed to mathematical stimuli: e.g., heart rate and skin conductance (Dew et al., 1984); cortisol secretion (Pletzer et al., 2010; Mattarella-Micke et al., 2011) and especially brain imaging measures ranging from EEG recordings (Núñez-Peña and Suárez-Pellicioni, 2014, 2015); to functional MRI (Lyons and Beilock, 2012b; Young et al., 2012; Pletzer et al., 2015).

PHYSIOLOGICAL MEASURES: CORTISOL SECRETION

Cortisol secretion is a response to stress (Hellhammer et al., 2009), and therefore might be expected to be higher in people with high levels of mathematics anxiety when presented with mathematical stimuli or activities. Studies do indeed support this view, as well as giving some clues about the interactions between mathematics anxiety and other characteristics.

Pletzer et al. (2010) investigated people's changes in cortisol level in response to the stress of a statistics examination, and the relationship between these changes and their actual examination performance. They were also assessed on a questionnaire measure of mathematics anxiety (a version of the MARS) and on tests of magnitude judgements and arithmetic. With a few exceptions who showed other patterns, most participants either showed an increase in cortisol from the basal level just before the examination, and a decrease afterwards, or a decrease in cortisol from the basal level both before and after the examination. Neither absolute levels or cortisol nor patterns of change in cortisol production correlated with the MARS, with the arithmetical tests, or with performance in the examination itself. However, the cortisol response to the examination did influence the association of other predictor variables and statistics performance. Mathematics anxiety and arithmetic abilities predicted statistics performance significantly in the group who showed an increase in cortisol production before the examination with a subsequent decrease, but not in the group that showed a consistent decrease.

Mattarella-Micke et al. (2011) measured cortisol secretion levels just before and after participants were presented with challenging mathematics problems. They also assessed their working memory. The performance of individuals with low working memory scores was not associated with mathematics anxiety or cortisol secretion. For people with higher working memory scores, those with high mathematics anxiety showed a negative relationship between cortisol secretion and mathematics performance, while those with low mathematics anxiety showed a positive relationship between cortisol secretion and mathematics performance.

Thus, in the studies carried out so far, the relationship between mathematics anxiety and cortisol response are not absolutely straightforward. It appears that the cortisol secretion profile modulates the relationship between mathematics anxiety and mathematics performance, while mathematics anxiety modulates the relationship between cortisol and performance. Thus, there are modulatory relationships between these measures, which are well worth studying further; but no evidence as yet that cortisol response is a good indicator of mathematics anxiety, or should replace traditional questionnaires.

PHYSIOLOGICAL MEASURES: WHAT CAN MEASURES OF BRAIN FUNCTION TELL US ABOUT MATHEMATICS ANXIETY?

Attempts at physiological measures of mathematics anxiety have more commonly involved some form of recording of brain function. Dehaene (1997, p. 235) argues that the neuroscience of mathematics can and must involve emotional factors: "...(C)erebral function is not confined to the cold transformation of information according to logical rules. If we are to understand how mathematics can become the subject of so much passion or hatred, we have to grant as much attention to the computations of emotion as to the syntax of reason." It is, however, only quite recently that we have had the ability to carry out functional brain imaging with sufficient numbers of participants to be able to examine correlations between individual differences in brain function and individual differences in behavioral characteristics. It is even more recently that we have been able to apply functional brain imaging to children.

It is important to remember that finding neural correlates of behavioral characteristics does not mean that the brain characteristics are *causing* the behavioral characteristics. They are at least as likely to be *reflecting* the behavioral characteristics. Nevertheless, examining brain-based correlates of mathematics anxiety may give us some clues as to the cognitive characteristics involved, even if it does not tell anything about the direction of causation. They may also give us ways of assessing mathematics anxiety without needing to rely on self-report measures.

PHYSIOLOGICAL MEASURES: EEG/ERP

Núñez-Peña and Suárez-Pellicioni (2014, 2015) carried out both ERP and behavioral measures of numerical processing in people with high and low mathematics anxiety as measured on the MARS questionnaire. In a magnitude comparison test, people with high mathematics anxiety had slower reaction times and showed larger size and distance effects than those with low mathematics anxiety. ERP measures showed that those with high mathematics anxiety showed higher amplitude in frontal areas for both the size and distance effects than did those with low mathematics anxiety: a component which has been proposed to be associated with numerical processing. They also looked at two-digit addition in people with high and low mathematics anxiety. They were presented with correct and incorrect answers to such problems, and asked to say whether each answer was right or wrong. Participants with high mathematics anxiety were significantly slower and less accurate than those with low mathematics anxiety. ERP analysis showed that people with high mathematics anxiety showed a P2 component of larger amplitude than did people with low mathematics anxiety. This component had been previously found to be associated with devoting attentional resources to emotionally negative stimuli. Thus, the studies suggest that people with high mathematics anxiety may be devoting extra attentional resources to their worries, possibly at the expense of task performance, though the direction of causation cannot be determined from a correlational study.

PHYSIOLOGICAL MEASURES: FUNCTIONAL MRI

There has been much evidence that stress affects the activation levels of regions of the prefrontal cortex, possibly interfering with the working memory functions associated with this area (Qin et al., 2009). These effects have been shown to be greater in people with high levels of general anxiety as a trait. For example, Bishop (2009) found that, even in the absence of threat stimuli, people with high trait anxiety showed less prefrontal activation in attentional control tasks than people with lower trait anxiety, and this was associated with less efficient performance. Basten et al. (2012) found that high trait anxiety was associated with high activation of the right dorsolateral prefrontal cortex (dLPFC) and left inferior frontal sulcus, which are generally found to be implicated in the goal-directed control of attention, and with strong deactivation of the rostral-ventral anterior cingulate cortex, a key region in the brain's default-mode network. The authors suggested that these activation patterns were likely to be associated with inefficient manipulations in working memory.

Lyons and Beilock (2012a) carried out functional brain imaging studies with adults with high and low mathematics anxiety. The individuals with high mathematics anxiety tended to show less activity in the frontal and parietal areas in anticipating and carrying out mathematical tasks than did less anxious individuals. They also did less well in the mathematical tasks. However, there was a subgroup, that did show strong activation of these areas when anticipating a mathematics task, and these individuals performed much better than those who did not show such activation, and almost as well as those with low mathematics anxiety. This group of individuals also showed high activation during the mathematics task, not so much of the parietal and other cortical areas associated with arithmetic, but of subcortical areas associated with motivation and assessment of risk and reward. The authors suggested that the deficit in performance of individuals with high mathematics anxiety might be determined by their response and interpretation of their anxiety response, instead of the magnitude of those anxiety response or their mathematics skills *per se*.

Pletzer et al. (2015) carried out an fMRI study of two groups of people, matched for their mathematical performance on tests of magnitude judgment and arithmetic, but differing in levels of mathematics anxiety, as measured by a version of the MARS. Eighteen participants scored high and 18 low on the measure of mathematics anxiety. They underwent fMRI when carrying out two numerical tasks: number comparison and number bisection. For comparison, they were also given brief non-numerical cognitive tasks involving verbal reasoning and mental rotation. The groups did not differ in their brain activation patterns for the non-numerical tasks. In the numerical tasks, they did not differ with regard to the activation of areas known to be involved in number processing, such as the intraparietal sulcus (similar to findings of Lyons and Beilock, 2012a,b) suggesting that performance deficits of high mathematics anxious individuals were unlikely to be due to lower mathematics skills; but the group with high mathematics anxiety showed more activity in other areas of the brain, especially frontal areas associated with inhibition. This suggests that processing efficiency may be impaired in people with high mathematics anxiety, requiring more effort to inhibit incorrect responses. The differences seemed to occur specifically for items that required magnitude processing, and were not found for items that involved multiplication and could readily be solved by fact retrieval.

Recently, functional brain imaging studies have indicated that 7- to 9-year-old children are already showing some of the same neural correlates of mathematics anxiety as adults. Young et al. (2012) carried out a functional MRI study with 7- to 9-year-old children, and found that mathematics anxiety was associated with high levels of activity in right amygdala regions that are involved in processing negative emotions and reduced activity in posterior parietal and dorsolateral prefrontal cortex regions associated with mathematical problem-solving (the latter finding was in contrast to Pletzer et al., 2015, Lyons and Beilock, 2012a,b who found no activation differences in these areas). Children with high mathematics anxiety also showed greater functional connectivity between the amygdala and areas in the ventromedial prefrontal cortex that are associated with negative activity was also positively correlated with task activity in two subcortical regions: the right caudate nucleus and left hippocampus, both of which are known to be involved in memory processes. Crucially, these brain activity differences were mainly found, not during the actual mathematics task, but during the cue that preceded it (similar to Lyons and Beilock, 2012b). Thus, the control processes that influence whether mathematics anxiety will inhibit performance seem to occur at the time of anticipation of the mathematics task, rather than during the task itself.

These studies have led to some interesting proposals about the most effective timing of cognitive treatments for mathematics anxiety. In particular, Lyons and Beilock (2012b, p. 2108) have proposed, on the basis of the above-mentioned brain-imaging studies and their own findings (greater activation in areas associated with visceral threat detection and pain perception with higher mathematics anxiety before but not during mathematics performance), that "emotional control processes that act early on the arousal of negative affective responses (e.g., reappraisal) are more effective at mitigating these responses and limiting concomitant performance decrements than explicit suppression of these responses later in the affective process." As we shall see, this has implications for treatments.

FACTORS THAT INFLUENCE MATHEMATICS ANXIETY: GENETICS

So far, we have been discussing the nature and assessment of mathematics anxiety, without much reference to the factors that influence it. One potential factor that has been investigated is genetics. Wang et al. (2014) carried out behavioral genetic studies of mathematics anxiety in a sample of 514 twelve-year-old twin pairs. They were given the Elementary Students version of the MARS as a measure of mathematics anxiety; the Spence Children's Anxiety Scale as a measure of test anxiety; a mathematical problem solving subtest of the Woodcock-Johnson III Tests of Achievement; and a reading comprehension test from the Woodcock Reading Mastery Test. Mathematics anxiety correlated significantly with general anxiety, and also correlated negatively with both mathematical problem solving and reading comprehension, while general anxiety did not correlate significantly with either academic measure. Univariate and multivariate behavioral genetic modeling indicated that genetic factors accounted for about 40% of the variance in mathematics anxiety, with most of the rest being explained by non-shared environmental factors.

It is unlikely that there are genetic factors specific to mathematics anxiety. Rather, the multivariate analyses suggested that mathematics anxiety was influenced by the genetic and environmental risk factors involved in general anxiety, and the genetic factors involved in mathematical problem solving. Thus, mathematics anxiety may result from a combination of negative experiences with mathematics, and predisposing genetic risk factors associated with both mathematical cognition and general anxiety.

GENDER AND MATHEMATICS ANXIETY

One of the factors that has received most study with regard to mathematics anxiety is that of gender. Much recent research indicates that males and females, in countries that provide equal education for both genders, show little or no difference in actual mathematical performance (Spelke, 2005). However, they do indicate that females tend to rate themselves lower and to express more anxiety about mathematics (Wigfield and Meece, 1988; Hembree, 1990; Else-Quest et al., 2010; Devine et al., 2012), though such differences are not huge (Hyde, 2005). Most studies suggest such gender differences only develop at adolescence, and that primary school children do not exhibit gender differences in mathematics anxiety (Dowker et al., 2012; Wu et al., 2012; Harari et al., 2013) though even in the younger age group boys often rate themselves higher in mathematics than girls do (Dowker et al., 2012). This increased anxiety may come from several sources, including exposure to gender stereotypes, and the influence and social transmission of anxiety by female teachers who are themselves anxious about mathematics (Beilock et al., 2010).

It may also be related to more general differences in anxiety between males and females. Many studies indicate that females tend to show higher levels of trait anxiety and the closely related trait of Neuroticism than males (e.g., Feingold, 1994; Costa et al., 2001; Chapman et al., 2007) and show higher prevalence of clinical anxiety disorders (McLean et al., 2011). They have been found to show greater anxiety than males even in subjects where their actual performance tends to be higher than that of males, such as foreign language learning (Park and French, 2013).

Also, males tend to show more confidence and rate themselves higher in a number of domains than females do (e.g., Beyer, 1990; Beyer and Bowden, 1997; Jakobsson et al., 2013). Thus, it is not surprising that this should also apply to mathematics, and, given the associations between anxiety and self-rating, that it might contribute to gender differences in mathematics anxiety.

However, there is some evidence that gender differences in mathematics anxiety cannot be reduced to gender differences in general academic self-confidence or in test anxiety. Devine et al. (2012) found that mathematics anxiety has an effect on mathematics performance, even after controlling for general test anxiety, in girls but not in boys. They asked 433 British secondary school children in school years 7, 8, and 10 (11-to 15-year-olds) to complete mental mathematics tests and Mathematics Anxiety and Test Anxiety questionnaires. Boys and girls did not differ in mathematics performance; but girls had both higher mathematics anxiety and higher test anxiety. Both girls and boys showed a positive correlation between mathematics anxiety and test anxiety and a negative correlation between mathematics anxiety and mathematics performance. Both boys and girls showed a negative correlation between mathematics anxiety and mathematics performance. However, regression analyses showed that for boys, this relationship disappeared after controlling for general test anxiety. Only girls continued to show an independent relationship between mathematics anxiety and mathematics performance.

By contrast, Hembree (1990) suggested that math anxiety is more negatively related to achievement in males than in females, and some other studies suggested that there are no gender differences in the relationship between mathematics anxiety and performance (Meece et al., 1990; Ma, 1999; Wu et al., 2012). However, most such studies have not controlled for general test anxiety. Gender effects on the relationship between mathematics anxiety and performance may also depend on whether one is examining the cognitive or affective component of mathematics anxiety, and on what aspects of mathematics are involved. Indeed, Miller and Bichsel (2004) found that mathematics anxiety was more related to basic mathematics scores in males, but to applied mathematics scores in females. More research is needed as to what influences gender differences in both mathematics anxiety itself, and in its influence on performance.

It is unlikely that such gender differences are the result of gender differences in working memory, as on the whole, studies show relatively few gender differences in working memory (Robert and Savoie, 2006) though some studies suggest that males may be better at visuo-spatial working memory and females at verbal working memory (Robert and Savoie, 2006). Intriguingly, Ganley and Vasilyeva (2014) carried out a mediation analysis that suggested that mathematics anxiety seemed to affect visuo-spatial working memory more in female than male college students, and that this led to a greater decrement in mathematics performance. However, since other studies suggest that mathematics anxiety affects verbal more than visuo-spatial working memory (DeCaro et al., 2010), there is still much room for further research here.

One possible explanation for greater mathematics anxiety in females than males is *stereotype threat.* Stereotype threat occurs in situations where people feel at risk of confirming a negative stereotype about a group to which they belong. In the domain of mathematics anxiety, this usually refers to females being reminded of the stereotype that males are better at mathematics than females, though it can also occur with regard to other stereotypes. For example, Aronson et al. (1999) found that white American men performed less well in mathematics when they were told that Asians tend to perform better in mathematics than white people, than when they were not exposed to this stereotype.

Most of the studies of the effects of stereotype threat on mathematics anxiety are somewhat indirect: they indicate that mathematics performance is worse when people are exposed to stereotype threat, but do not usually include direct measures of mathematics anxiety. While one likely explanation for the effects of stereotype threat is that it increases mathematics anxiety, there are other possibilities: e.g., that participants choose to conform to social expectations. This caution must be borne in mind when considering the evidence about the effects of stereotype threat on performance.

Schmader (2002) and Beilock et al. (2007) found that women performed less well on an arithmetic task if they were told that the researchers were studying why women do more poorly than men. Beilock et al. (2007) noted that, as is often found in studies of mathematics anxiety, the effect only occurred for problems that required the significant use of working memory resources.

Johns et al. (2005) gave participants a mathematics test under three conditions: one without any reference to gender stereotypes; one where they were told that the researchers were studying reasons why women performed less well in mathematics; and one where they were exposed to the same gender stereotype, but also taught explicitly about the nature of stereotype threat in this context, and how it could increase women's anxiety when doing mathematics. Females performed less well than men in the condition where the gender stereotype was presented without explanation, but there were no gender differences either in the condition where no gender stereotype was presented *or* in the condition where they were taught explicitly about the stereotype threat.

However, the effect of stereotype threat is not always found, especially in children. Ganley et al. (2013) carried out three studies with a total sample of 931 school children ranging from fourth to twelfth grade, and using several different methods from the implicit to the highly explicit to induce stereotype threat. There was no evidence of any effect of stereotype threat on girls' performance in any of these studies. It may be that stereotype threat only exerts an influence in very specific circumstances, or on the other hand that it always occurs and exerts an influence under all circumstances, so that the experimental manipulations exerted no additional effect. It may also be that the importance of stereotype threat has been overestimated at least with regard to children; or that the effects were greater in the past than now, due to changes in social attitudes.

Moreover, it may be that gender stereotypes are affecting not so much mathematics anxiety itself as self-perceptions of mathematics anxiety. Goetz and colleagues gave secondary school pupils questionnaires about mathematics anxiety as a *trait*, and also about their anxiety as a *state* during a mathematics class (Goetz et al., 2013; Bieg et al., 2015). Both boys and girls tended to report higher trait anxiety than state anxiety, but girls did so to a much greater extent. Girls reported higher trait anxiety than boys in both studies, but higher state anxiety only in one of the studies. One possible conclusion that girls do not in fact experience so much more mathematics anxiety than boys, but that due to gender stereotypes they *expect* to experience more mathematics anxiety, and this in itself may discourage them from pursuing mathematics activities and courses.

FACTORS THAT AFFECT MATHEMATICS ANXIETY: AGE

On the whole, mathematics anxiety appears to increase with age during childhood. Most studies suggest that severe mathematics anxiety is uncommon in young children, though some researchers have found significant mathematics anxiety even among early primary school children (Wu et al., 2012). This apparent increase in mathematics anxiety with age is consistent with findings that show that other attitudes to mathematics change with age. Unfortunately, they tend to deteriorate as children get older (Ma and Kishor, 1997; Dowker, 2005; Mata et al., 2012). Blatchford (1996) found that two-thirds of 11-years-olds rate mathematics as their favorite subject, but that few 16-year-olds do so. Some studies suggest that the deterioration of attitudes begins even before the end of primary school (Wigfield and Meece, 1988).

There are a number of reasons why mathematics anxiety might increase with age: some relating more to the "anxiety" and some more to the "mathematics." One reason is that general anxiety appears to increase with age during childhood and adolescence could also reflect increases in tendency to general anxiety. For example, it is generally found that the onset of clinical anxiety disorders peaks in early adolescence (Kiessler et al., 2005) though it is possible that such disorders in younger children are under-diagnosed due to lack of clear and appropriate diagnostic methods (Egger and Angold, 2006). It may be that a factor such as increasing intolerance of uncertainty or increasing awareness of social comparison is leading to both increased general anxiety and to increased mathematics anxiety in particular.

Reasons more specifically relating to mathematics may include exposure to other people's negative attitudes to mathematics; to social stereotypes, for example about the general difficulty of mathematics or about supposed gender differences in mathematics; to experiences of failure or the threat of it; and/or to changes in the content of mathematics itself. Arithmetic with larger numbers that make greater demands on working memory, and more abstract non-numerical aspects of mathematics, may arouse more anxiety than the possibly more accessible aspects of mathematics encountered by younger children.

Moreover, the relationships between attitudes and performance may change with age. A meta-analysis by Ma and Kishor (1997) indicated that the relationship between attitudes and performance increases with age. Some studies suggest that among young children, performance is not significantly related to anxiety (Cain-Caston, 1993; Krinzinger et al., 2009; Dowker et al., 2012; Haase et al., 2012), but is more related to liking for mathematics and especially to self-rating. However, different studies give conflicting results; and some studies do show a significant relationship between anxiety and performance in young children (Dossey et al., 1988; Newstead, 1998; Wu et al., 2012; Ramirez et al., 2013; Vukovic et al., 2013).

There are at least three possible explanations for the conflicting findings. One is that the results may vary according to the aspect of mathematics anxiety that is being studied. Studies that base their measures on Richardson and Suinn (1972). Mathematics Rating Scale (MARS) or MARS-Elementary (Suinn et al., 1988) have tended to show such a relationship even in young children (Wu et al., 2012; Vukovic et al., 2013), and this could reflect the fact that such measures tend to focus on the affective dimension of mathematics anxiety. Those that have used the Mathematics Anxiety Questionnaire (MAQ) developed by Thomas and Dowker (2000) have tended not to show such a relationship in younger children (Krinzinger et al., 2007, 2009; Dowker et al., 2012; Haase et al., 2012; Wood et al., 2012), which could reflect the fact that this measure places more emphasis on the cognitive ("worry") aspect of mathematics. The few studies that have included both dimensions of mathematics anxiety have suggested that performance in young children is related to the affective but not to the cognitive dimension (Harari et al., 2013), whereas studies of older children and adults suggest that performance is related to both, but is more strongly related to the affective dimension (Wigfield and Meece, 1988; Ho et al., 2000). More research is needed on how the relationship changes with age between performance and different components of mathematics anxiety.

A second explanation is that mathematics anxiety becomes more closely related to mathematics performance because of changes in working memory. Working memory of course increases with age in childhood (Henry, 2012), which could affect the relationship between anxiety and performance. One study does suggest that the relationship between anxiety and performance is greater in children with higher than lower levels of working memory. Vukovic et al. (2013) carried out a longitudinal study of 113 children, who were followed up from second to third grade. Mathematics anxiety was measured by items from the MARS-Elementary and from Wigfield and Meece's (1988) MAQ. Mathematics anxiety was negatively related to performance in calculation but not geometry. It was also negatively correlated with pupils' improvement from second to third grade, but only for children with higher levels of working memory. This is at first sight surprising given that working memory is generally positively correlated with mathematical performance, and especially in view of the theory that mathematics anxiety impedes performance by overloading working memory. We would suggest that a likely explanation is that among younger elementary school children, only those with high levels of working memory are already using mathematical strategies that depend significantly on working memory, and that therefore these may be the children whose progress is most impeded by mathematics anxiety. This could be one explanation for mathematics anxiety being more correlated with performance more in older than in younger children.

A third possible explanation is cultural. The studies that do show a relationship between mathematics anxiety and achievement among young children tend to be from the USA, though this could of course be a coincidence, and there are at present no obvious reasons why the relationship should be stronger in the USA than elsewhere. Nevertheless, there is evidence more generally for cultural influences on mathematics anxiety.

CULTURE, NATIONALITY, AND MATHEMATICS ANXIETY

Some aspects of attitudes to mathematics seem to be common to many countries and cultures: e.g., the tendency for young children to like mathematics, and for attitudes to deteriorate with age (Ma and Kishor, 1997; Dowker, 2005). However, different countries differ not only in actual mathematics performance, but also in liking mathematics; in whether mathematics is attributed more to ability or effort; and how much importance is attributed to mathematics (Stevenson et al., 1990; Askew et al., 2010).

Some of these differences could affect mathematics anxiety, though the direction is not completely predictable. Children in high-achieving countries could be low in mathematics anxiety because they are doing well (and/or may do well because they are not impeded by mathematics anxiety). On the other hand, they could be high in mathematics anxiety, because such countries often attach high importance to mathematics and to academic achievement in general, making failure more threatening; and because such children are likely to be comparing themselves with high-achieving peers, rather than with lower-achieving children in other countries. Lee (2009) investigated mathematics anxiety scores in a variety of countries and found that the relationship between a country's overall mathematics achievement level, and the average level of mathematics anxiety among children in that country, was not consistent. Children in high-achieving Asian countries, such as Korea and Japan, tended to demonstrate high mathematics anxiety; while those in high-achieving Western European countries, such as Finland, the Netherlands, Liechtenstein, and Switzerland tended to demonstrate low mathematics anxiety. At present, the reason for these differences is not clear. They may be related to the fact that pressure to do well in examinations is probably significantly greater in Asian countries (e.g., Tan and Yates, 2011). They could also be related to some as yet undetermined specific aspects of the educational systems or curricula.

Another possible reason could involve cultural or ethnic differences either in willingness to admit to mathematics anxiety, or in the nature of the relationship between mathematics anxiety and mathematics performance. Several studies have suggested that ethnic minority students express more positive attitudes to mathematics than white pupils both in the USA (Catsambis, 1994; Lubienski, 2002) and in the UK (National Audit Office, 2008), which did not conform to actual differences in performance. However, the meta-analysis of Ma (1999) showed no ethnic differences with regard to the relationship between anxiety and performance.

There is overwhelming evidence that both the socio-economic status of individuals and the economic position of countries have a very large influence on mathematical participation and achievement (e.g., Chiu and Xihua, 2008), However, there has been little research specifically on the influence of socio-economic status on mathematics anxiety or attitudes to mathematics; and the research that has been done does not suggest a very strong SES effect on these variables (Jadjewski, 2011).

POTENTIAL TREATMENTS OF MATHEMATICS ANXIETY

Research has already told us a lot about the nature of emotions and attitudes toward mathematics. So far, it tells us less about how such attitudes can be modified, and how mathematics anxiety may be treated, or, ideally, prevented. It is likely that early interventions for children with mathematical difficulties may go some way toward preventing a vicious spiral, where mathematical difficulties cause anxiety, which causes further difficulties with mathematics. Parents and teachers could attempt to model positive attitudes to mathematics and avoid expressing negative ones to children. This may, however, be difficult if the parents or teachers are themselves highly anxious about mathematics. There could be greater media promotion of mathematics as interesting and important. However, much more research is needed on the effectiveness of different strategies for improving attitudes to mathematics. In such research, it must be taken into account, both that mathematics has many components and that different strategies might be effective with different components; and that improving attitudes to mathematics means not only reducing anxiety and other negative emotions toward mathematics, but increasing positive emotions toward mathematics.

Treatments of already-established mathematics anxiety may involve both mathematics interventions as such, and treatments for anxiety such as systematic desensitization and cognitive behavior therapy. So far, no miracle cure seems to be in sight. However, there are new methods, based on recent research findings that appear to be promising.

In particular, researchers have recently attempted to use findings about the cognitive aspects of mathematics anxiety, and about cognitive treatments of anxiety more generally, to develop techniques involving reappraisal of the anxiety-provoking situation. A few recent studies suggest that instructing people to reappraise the nature and consequences of mathematics anxiety may reduce the negative effects, breaking a vicious circle, whereby people feel that their anxiety will worsen their performance or is a signal of inability to carry out the tasks. Johns et al. (2008) and Jamieson et al. (2010) found that informing people that arousal could actually improve performance led to better mathematics performance than in a control condition.

Beilock and colleagues have developed a promising intervention for mathematics anxiety that amounts to "writing out" the negative affect and worry (Ramirez and Beilock, 2011; Park et al., 2014). The researchers drew on previous findings that writing about traumatic and highly emotional events lowered ruminating behavior in individuals with clinical depression (Smyth, 1998). A possible mechanism for this could be that writing enables a form of reappraisal that interrogates the need to worry in the first place. This in turn frees working memory resources consumed by worrying, which can be deployed toward task performance. Ramirez and Beilock (2011) tested this proposition both in a laboratory environment and also in a high-stakes field experiment (i.e., an exam). Both the laboratory and field experiments showed that writing about one's worries before academic performance significantly improved performance compared to a control condition (e.g., writing about untested exam material). An exam can be stressful for anyone taking it. Most interesting, therefore, was the finding that 10 min of expressive writing before an exam was only beneficial for individuals with high test anxiety, compared to control writing. Individuals with low test anxiety did not experience any particular benefits from expressive writing. The authors attribute this to the extent to which individuals with high and low test anxiety differ in worrying about exams. Individuals with lower test anxiety, who presumably worry less, would therefore write about fewer worries during an expressive writing exercise. In other words, there is simply less worry that needs to be "written out" for individuals with low test anxiety, in contrast to individuals with high mathematics anxiety. The potential of this kind of intervention to facilitate a level playing field during exams is potentially large. Indeed, students in the expressive condition outperformed those in the control condition by 6%. In letter grades, the expressive condition students earned a B+ on average, while those in the control condition earned a B–. Could this kind of intervention be useful for mathematics anxiety? The same group of authors has suggested that this may be the case. In a recent paper, Park et al. (2014) explored the influence of expressive writing on the link between mathematics anxiety and mathematics performance. Parallel to the Ramirez and Beilock (2011) results, Park et al. (2014) found that expressive writing ameliorated performance on tasks of modular arithmetic (specially developed working memory-intensive mathematics problems) in high mathematics anxiety individuals compared to a control writing task. As stated earlier in this paper, one of the central tenets of current theories of mathematics anxiety is that the negative emotional state and associated ruminations absorb *working memory* resources necessary for task completion. Expressive writing seems to disrupt the negative emotional cognitions, and allows individuals to engage with the mathematical tasks rather than the attendant anxiety. Unlike Ramirez and Beilock (2011), Park et al. (2014) did not test these propositions in the field with an actual mathematics exam. Therefore, the benefit of expressive writing on mathematics examination performance remains a presumption in need of verification. However, a note of cautious optimism is permissible, given both the promising results from the earlier field experiments as well as evidence of higher performance on working memory-intensive problems reported in Park et al. (2014). Future research can easily investigate this possibility, as the only requirement is that proctors instruct students to engage in a writing task 10 min before the start of an exam.

Recently, the potential of cognitive tutoring to intervene with mathematics anxiety has been explored. Supekar et al. (2015) examined whether an intensive, 8-week one-on-one math-tutoring programme, MathWise that was developed by Fuchs et al. (2013) to improve mathematical skills could remediate math anxiety of children aged 7–9 years old. Children underwent three sessions of 40–50 min mathematics tutoring per week. They reported math anxiety levels using the Scale for Early Mathematics Anxiety (Wu et al., 2012) and were scanned using fMRI before and after training. During scanning, children performed on an arithmetic problem-solving task (Addition task) and number-identification (Control task). This study found that tutoring reduced math anxiety scores and remediated aberrant functional responses and connectivity in emotion-related circuits associated with the basolateral amygdala in children with high mathematics anxiety, but not those with low mathematics anxiety. In particular, they found that children with greater tutoring-associated decreases in their amygdala activity showed higher reductions in mathematics anxiety. The authors proposed that similar to models of exposure-based therapy for anxiety disorders, sustained exposure to mathematical stimuli could reduce mathematics anxiety, possibly through modulating the role of the amygdala. Together, this study showed that a relatively short and intensive one-on-one cognitive tutoring could remediate mathematics anxiety through modulation of neural functions.

As highlighted by Sokolowski and Necka (2016) however, interpretations of these findings should consider that since children were categorized through the extreme group approach (into high or low math-anxious using a median-split of pre-test SEMA scores) and were not recruited on the basis of their math anxiety levels, it is possible that children with nearly average SEMA scores might have been included in the high math anxious group (which is typically defined, for example by Ashcraft and Kirk (2001), as the highest 20% of this population). Such classification might affect the interpretations of "aberrant neural responses" attributed to children with high mathematics anxiety. Nonetheless, Supekar et al. (2015) provided a proof-of-concept that behavioral interventions with simultaneous neural, social and cognitive assessments could contribute to our understanding of the relationship between individual differences and efficacy of interventions.

Another potential form of treatment, which is just beginning to be explored, involves non-invasive brain stimulation. Non-invasive brain stimulation techniques are used by researchers to modulate neural activity on broad areas of the cortex. Transcranial electrical stimulation (tES) has emerged as a painless technique in which mild electrical currents are applied to the scalp and can be used to both upregulate and downregulate neuronal activity underneath the cortex.

Might such a technique be useful as an intervention for mathematics anxiety? As stated above, some brain imaging research has examined the neurophysiological signatures of mathematics anxiety. These include abnormal amygdala activation (Young et al., 2012) associated with fear processing, activation of the dorsoposterior insula, associated with pain perception (Lyons and Beilock, 2012a), and hypoactivation of regions in the frontoparietal network such as the dorsolateral prefrontal cortex, associated with both cognitive control of negative emotions and with mathematical performance (Lyons and Beilock, 2012b). Transcranial electrical stimulation enables researchers to modulate cortical activity in regions that may facilitate greater emotional control over the negative emotional response to mathematical stimuli, thereby improving performance. Transcranial direct current stimulation (tDCS) is the most widely used form of tES. tDCS is a non-invasive and painless neuromodulation technique wherein a low direct current, usually between 1 and 2 mA, is transmitted into cortical tissue through scalp-electrodes (Nitsche et al., 2008; Cohen Kadosh, 2013; Krause and Cohen Kadosh, 2014). The electrical signals in tDCS alter neuronal polarization, thereby manipulating the probability that the targeted neurons will fire; typically, anodal stimulation is known to facilitate neural firing, while cathodal stimulation inhibits neuronal firing of the stimulated cortical region (Nitsche and Paulus, 2000). In sham (placebo) stimulation, a burst of current is provided and turned-off, generating the same physical sensations as real stimulation (e.g., mild itching, burning, tingling, or stinging), but producing no change in cortical excitability. This serves as a reliable blinding method, and participants are generally unable to distinguish between real and sham stimulation (Gandiga et al., 2006). The brain region usually targeted in emotion-related tDCS research is the dorsolateral prefrontal cortex (dlPFC), which is implicated in working memory and affective regulation (Peña-Gómez et al., 2011), and is closely involved in the response and control of stress (Cerqueira et al., 2008).

Sarkar et al. (2014) investigated the effects of tDCS to the dlPFC on mathematics anxiety. High mathematics anxiety individuals received 1 mA of tDCS for 30 min (or 30 s, in the placebo condition) to their left and right dorsolateral prefrontal cortices to enhance cognitive control over the negative emotional response elicited by mathematical stimuli. A low mathematics anxiety group received the same treatment. Sarkar et al. (2014) also examined changes in salivary cortisol, mentioned above as a possible physiological measure of anxiety. Anodal and cathodal stimulation were applied to the left and right dlPFC, respectively. In their study, Sarkar et al. (2014) found that, compared to sham stimulation, real tDCS lowered reaction times in the arithmetic decision task for individuals with high mathematics anxiety. They found the opposite pattern for low mathematics anxiety participants, who were slower in real compared to sham stimulation. The cortisol changes mirrored the behavioral changes. Compared to sham stimulation, high mathematics anxiety participants showed a decline in salivary cortisol concentrations from pre- to post-test during real tDCS. For the low mathematics anxiety group, salivary cortisol concentrations declined from pre-test to post-test only during sham tDCS, but not during real stimulation. This suggests tDCS might be able to alleviate the stress associated with mathematics anxiety, thereby improving mathematical performance in individuals with high mathematics anxiety. It is still necessary to be cautious about this possibility for several reasons. Firstly, as discussed above, the relationship between cortisol secretion and mathematics anxiety may not be totally straightforward. Secondly, the ecological validity of such intervention (e.g., as regards the training design and the practicality of using tDCS outside the laboratory) remains to be improved (Cohen Kadosh, 2014; Looi et al., 2016). In the context of mathematics anxiety, further research is needed to examine whether tDCS could enhance performance for individuals with high mathematics anxiety in real-life settings and examinations (e.g., high-stakes situations). Given that the arithmetic decision task used by Sarkar et al. (2014) only required participants to decide whether very basic mathematical equations were true or false (e.g., $8 \times 2 = 16$, true or false), future studies could adopt more complex, realistic tasks. Thirdly, the improvement on such tasks was to the degree of ~50 ms, significant in a laboratory context but hardly relevant to the types of situations where mathematics anxiety is most relevant. Since behavioral studies mostly observe the influence of mathematics anxiety on difficult maths tasks (see Artemenko et al., 2015 for a recent review) and tES appears to be more effective during difficult tasks (Popescu et al., 2016), future studies could investigate whether improvements of individuals with mathematics anxiety would be greater during more difficult tasks. Fourthly, since the dlPFC is involved in many functions, it is as yet unclear exactly which of these functions was crucially affected here: in particular, whether tDCS affected performance by influencing its role in emotional processing, or working memory, or both. Fifthly, the findings suggest that such treatments would need to be targeted to people who are high in mathematics anxiety, and that their indiscriminate application to people with lower mathematics anxiety might actually impair performance. Hence, research that examines the mechanisms of such effects (positive or negative; short- or long-term) is needed (Bestmann et al., 2015). Finally, behavioral effects are influenced by the parameters of tDCS. For example, while Sarkar et al. (2014) showed that tDCS applied during mathematical tasks benefited those with high mathematics anxiety and impaired performance of those with low mathematics anxiety, it remains to be investigated whether changing the parameters of stimulation (e.g., applying stimulation before or after mathematical tasks) would yield different behavioral outcomes (for a review of other factors, see Looi and Cohen Kadosh, 2015). Thus, these findings are merely the first, though a promising step in the development of tES as a potential intervention for mathematics anxiety.

SO WHAT REMAINS TO BE UNDERSTOOD?

During the last 60 years, we have acquired a much greater understanding of the phenomenon of mathematics anxiety. We have learned more about its correlation with mathematics performance, and for example how working memory may be involved in this. We have learned more about how it changes with age. We have learned more about its relationship to social stereotypes, especially with regard to gender. We have learned something about neural correlates of mathematics anxiety. We have learned something about possible ways to treat mathematics anxiety.

Thus, we have learned a significant amount about many specific aspects of mathematics anxiety. Our biggest need for further learning may involve not so much any specific aspect, as the ways in which the aspects relate to one another. How do the social aspects relate to the neural aspects? How do either or both of these relate to changes with age? How might appropriate treatment be related to age and to the social and cognitive characteristics of the individuals? And of course the perennial "chicken and egg" question: does mathematics anxiety lead to poorer performance, or does poor performance, with its resulting experiences of failure, lead to poorer performance (Carey et al., 2015)? Many more interdisciplinary, longitudinal and intervention studies will be needed to answer these questions. An ultimate goal of such research is to integrate findings from across the behavioral, cognitive and biological dimensions of this construct in order to produce a fuller description of mathematics anxiety as a trait that varies between individuals.

There are also more specific aspects of mathematics anxiety that need a lot more study. For example, although there has been a great deal of research on social influences on mathematics anxiety, most of this has involved one particular type of influence: gender stereotyping. Other influences also need more investigation. In particular, there needs to be more investigation of the role of pressures by parents and teachers for school achievement. This is especially true in view of the increasing importance of both mathematics as such and of academic qualifications in today's society; and in view of the increasing concern of governments in several countries about raising academic standards. The question arises of whether and at what point an increasing emphasis on mathematical achievement might have the negative and potentially counterproductive effect of increasing mathematics anxiety; and how this might be prevented. In this context, there needs to be more research on exactly how mathematics anxiety is related to motivation, and, in particular, whether there are differences in the relationships of intrinsic and extrinsic motivation to anxiety (Gottfried, 1982; Lepper, 1988; Ryan and Pintrich, 1997).

We hope that long before another 60 years have passed, research will have led to a greater understanding of mathematics anxiety, which will enable us to develop interventions and educational methods that will greatly reduce its incidence.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct, and intellectual contribution to the work, and approved it for publication.

FUNDING

We thank the Nuffield Foundation for financial support.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

MINI REVIEW
published: 01 September 2015
doi: 10.3389/fpsyg.2015.01333

Neural correlates of math anxiety – an overview and implications

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Math anxiety is a common phenomenon which can have a negative impact on numerical and arithmetic performance. However, so far little is known about the underlying neurocognitive mechanisms. This mini review provides an overview of studies investigating the neural correlates of math anxiety which provide several hints regarding its influence on math performance: while behavioral studies mostly observe an influence of math anxiety on difficult math tasks, neurophysiological studies show that processing efficiency is already affected in basic number processing. Overall, the neurocognitive literature suggests that (i) math anxiety elicits emotion- and pain-related activation during and before math activities, (ii) that the negative emotional response to math anxiety impairs processing efficiency, and (iii) that math deficits triggered by math anxiety may be compensated for by modulating the cognitive control or emotional regulation network. However, activation differs strongly between studies, depending on tasks, paradigms, and samples. We conclude that neural correlates can help to understand and explore the processes underlying math anxiety, but the data are not very consistent yet.

Keywords: math anxiety, math performance, processing efficiency, emotion regulation, negative emotions

OPEN ACCESS

Edited by:
Denes Szucs,
University of Cambridge, UK

Reviewed by:
Renata Melinda Heilman,
Babes-Bolyai University, Romania
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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *25 June 2015*
Accepted: *19 August 2015*
Published: *01 September 2015*

Citation:
Artemenko C, Daroczy G and Nuerk H-C (2015) Neural correlates of math anxiety – an overview and implications. Front. Psychol. 6:1333. doi: 10.3389/fpsyg.2015.01333

Math anxiety

Math anxiety is important in psychological research due to its consequences: avoidance of future mathematics related career (Ashcraft, 2002) and course choices (Chipman et al., 1992) or situations containing mathematics even in daily life context (Kohn et al., 2013). In the PISA 2012 study, overall 59% of students reported worrying that it will be difficult for them in mathematics classes, and 30% feel helpless when doing a mathematics problem (OECD, 2013). According to a definition by Richardson and Suinn (1972), math anxiety "involves feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations". It arises from unpleasant memories (Ma and Xu, 2004; Rubinsten and Tannock, 2010) and is related to math ability perception (Meece et al., 1990), self-regulation, and self-efficiency processes (Jain and Dowson, 2009) as well as to pedagogical factors (Rayner et al., 2009) and gender. For instance, girls generally report higher levels of math anxiety than boys (Devine et al., 2012).

Math anxiety is considered a multidimensional construct. One of the most well-known questionnaires – the mathematics anxiety rating scale (MARS) – differentiates between math test anxiety and numerical anxiety factors (Suinn and Winston, 2003). Besides this differentiation, the two dimensions most often confirmed are affective (emotional) and cognitive (worry) (Ho et al., 2000; Hopko, 2003; Harari et al., 2013). Furthermore, other factors such as behavioral, situational and physiological levels (Hembree, 1990; Krinzinger et al., 2009) may also play a role.

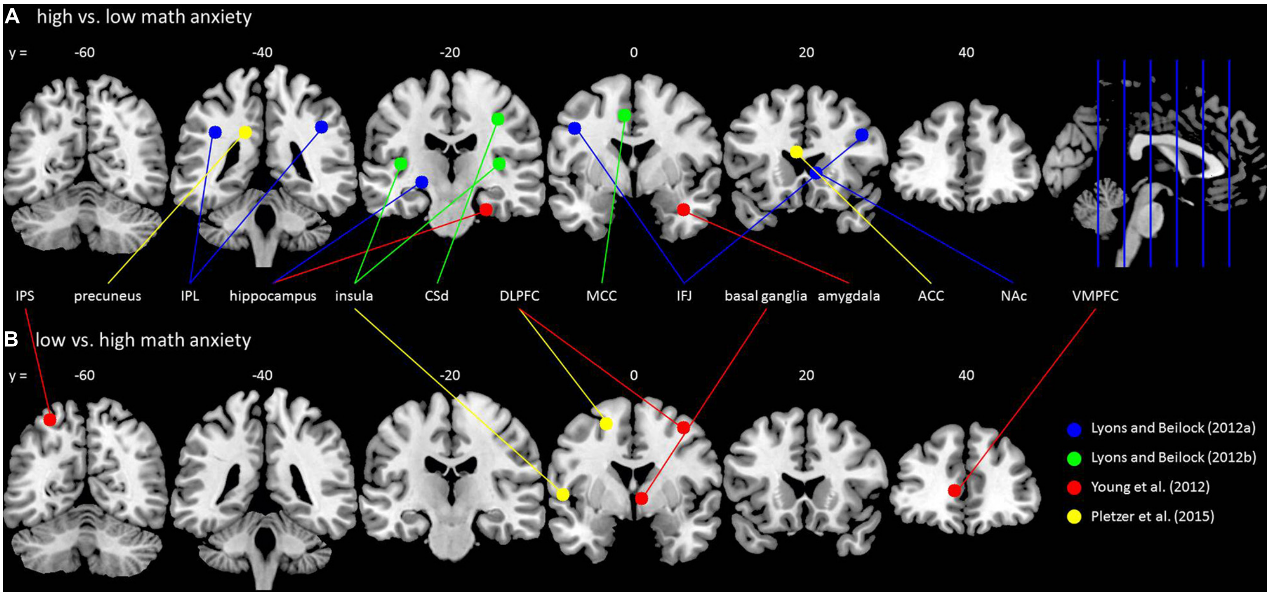

FIGURE 1 | Brain activation differences for math anxiety. (A) Brain areas showing higher activation in high math-anxious individuals compared to low math-anxious individuals. **(B)** Brain areas showing higher activation in low math-anxious individuals compared to high math-anxious individuals[1]. The circles are centered around the activation maximum of each cluster with a radius of 5 mm and are located on the *y*-slice next to its *y*-value (e.g., the slide with a *y*-value of 0 contains all activation maxima from $-10 \leq y \leq 10$) by using the software MRIcron (www.mricro.com/mricron). Different studies are indicated by different colors: blue – Lyons and Beilock (2012a); green – Lyons and Beilock (2012b); red – Young et al. (2012); yellow – Pletzer et al. (2015). Abbreviations are adapted from the original studies: ACC, anterior cingulate gyrus; CSd, dorsal segment of central sulcus; DLPFC, dorsolateral prefrontal cortex; IFJ, inferior frontal junction; IPL, inferior parietal lobe; IPS, intraparietal sulcus; MCC, midcingulate cortex; NAc, nucleus accumbens; VMPFC, ventromedial prefrontal cortex.

Math anxiety shares properties and mechanisms with test anxiety and general anxiety, but can also be distinguished from them (Baloglu, 1999; Kazelskis et al., 2000). Like other anxieties, high demands on cognitive resources and working memory capacities may moderate the relationship between anxiety and test performance (Owens et al., 2012). However, few studies control for other anxieties.

In summary, math anxiety is a common phenomenon which has considerable impact on the performance in math tasks (e.g., Ashcraft and Kirk, 2001). A solid neuroscientific understanding would provide better perspectives for interventions and therapies, but the underlying neurocognitive mechanisms are still unclear. In this mini review, we provide an overview of recent literature addressing the issue of math anxiety from a neuroscientific perspective (cf. **Figure 1**, **Table 1**). We will first address the neural correlates of the affective component of math anxiety and its regulation. Then, we turn to the neural correlates of the cognitive components of math anxiety, in particular processing efficiency. Finally, we outline how math anxiety and its neural correlates are related to math performance and finish with future perspectives.

[1] Note that further activation differences between high and low math-anxious individuals were observed in other brain areas such as the left anterior inferior frontal gyrus (Lyons and Beilock, 2012a), the supplementary motor area (Pletzer et al., 2015), the right primary somatosensory cortex (Young et al., 2012), and the dorsal segment of the right central sulcus (Lyons and Beilock, 2012b). But since the authors of the respective papers did not relate these activation differences to math anxiety, we did not include them in **Figure 1**, **Table 1** and the current review.

Affective Response in Math Anxiety

The affective component of math anxiety addresses the actual feelings and physiological reactions elicited by a math task in high math-anxious individuals. Thus, individuals with math anxiety reported negative attitudes such as dislike toward mathematics (Cornell, 1999), negative emotions such as tension (Richardson and Suinn, 1972), frustration (Hembree, 1990), and emotions related to learning outcomes such as shame, hopelessness (Pekrun et al., 2002). On a neural level, two networks representing the emotionality of math anxiety could be found: the pain network involving the insula (Lyons and Beilock, 2012b) and the fear network centered around the amygdala (Young et al., 2012).

Regarding the first, math anxiety elicited increased activation in the pain perception network including the bilateral dorso-posterior insula and mid-cingulate cortex (Lyons and Beilock, 2012b). The insula is supposedly associated with the subjective feeling of visceral threat for the upcoming math task and relief when confronted with a non-math task. The mid-cingulate cortex was not selective for pain perception *per se* but reflected similar emotionality. The pain-related activity was observed when high math-anxious individuals faced a math task but not during the math task itself, explaining that high math-anxious individuals try to avoid math. Additional analyses confirmed that math anxiety and not differences in math performance was responsible for the affective component.

TABLE 1 | Selected papers focusing on the neural correlates of math anxiety.

Study	Sample	Math anxiety	Groups	Tasks	Controlled variables	Results
fMRI studies						
Lyons and Beilock (2012a)	28 adults	sMARS	20% (out of $N = 108$)	Single-digit arithmetic verification task (simple/ complex, subtraction/ multiplication); control word task; cues before task	Trait anxiety, working memory	High math-anxious individuals show with decreasing math deficits increasing differences in IFJ and IPL before the math task and in right NAc and left hippocampus during math task (increasing emotion regulation leads to compensation of math deficit)
Lyons and Beilock (2012b)	28 adults	sMARS	ca. 50 %	Single-digit arithmetic verification task (simple/ complex, subtraction/ multiplication); control word task; cues before task	Trait anxiety, working memory	High math-anxious individuals show higher activation in bilateral dorso-posterior insula, MCC and right CSd (pain-related activity before math task)
Young et al. (2012)	46 7- to 9-year-old children	SEMA	50%	Single-digit arithmetic verification task (simple/ complex; addition/ subtraction); control number identification and passive fixation task	IQ, working memory, reading ability, math ability, trait anxiety	High math-anxious individuals show hyperactivity and abnormal effective connectivity of right amygdala extending into anterior hippocampus (processing negative emotions), less activation in IPS, right DLPFC, basal ganglia (less efficient task processing) and greater deactivation in VMPFC (emotion regulation)
Pletzer et al. (2015)	36 adults	MARS30-brief	25% (out of $N = 127$)	Two-digit number magnitude comparison task, number bisection task; control mental rotation task, control verbal reasoning task	Math ability	Low math-anxious individuals show moderately stronger deactivation within the task-related default mode network than high math-anxious individuals (less efficient processing), high math-anxious individuals did not activate left DLPFC, left inferior frontal gyrus and insula (task-irrelevant instead of task-relevant inhibitory control)
tDCS study						
Sarkar et al. (2014)	45 adults	Brief version of MARS	25% (out of $N = 165$)	Single-digit arithmetic verification task with affective primes (addition, subtraction, multiplication, division); control flanker task	Age, gender	Stimulating the DLPFC leads to better math performance and decreased cortisol concentrations in high math-anxious individuals (less stress), but impaired math performance and prevented cortisol decrease in low math-anxious individuals

(Continued)

TABLE 1 | Continued

Study	Sample	Math anxiety	Groups	Tasks	Controlled variables	Results
ERP studies						
Suárez-Pellicioni et al. (2013a)	26 adults	sMARS	25% (out of $N = 342$)	Single-digit arithmetic verification task (split effect; addition)	Math ability, trait anxiety, spatial visualization, reasoning ability, verbal comprehension ability, gender distribution	High math-anxious individuals show an enhanced and delayed P600/3b for large-split solutions (difficulty in inhibiting processing of irrelevant information and less processing efficiency)
Suárez-Pellicioni et al. (2013b)	34 adults	sMARS	25% (out of $N = 452$)	Single-digit numerical Stroop task; control classical Stroop task	Trait and state anxiety, years of formal education, age, handedness, ethnicity, gender distribution	High math-anxious individuals show an enhanced ERN (abnormal error monitoring), but no difference for CRN or Pe (normal generic response monitoring processes)
Suárez-Pellicioni et al. (2014)	34 adults	sMARS	25% (out of $N = 490$)	Single-digit numerical Stroop task	Trait and state anxiety, simple math ability, years of formal education, age, handedness, ethnicity, gender distribution	High math-anxious individuals show a tendency for an enhanced conflict sustained potential (stimulus conflict processing), no enhanced N450 and greater conflict sustained potential amplitude in conflict adaptation (attentional control deficit and distractibility)
Núñez-Peña and Suárez-Pellicioni (2014)	53 adults	sMARS	25% (out of $N = 629$)	Single-digit number magnitude comparison task (size effect, distance effect)	Trait anxiety, age, years of formal education, gender distribution, handedness, ethnicity	High math-anxious individuals show an enhanced ERP distance and size effect (less precise number magnitude representation)

The studies are sorted by method and include information on the analyzed sample size, the math anxiety questionnaire used, the cut-off value for a possible prescreening group for low vs. high math-anxious individuals, the numeric and the control task, controlled or matched variables between groups and the main results of the study.

ACC, anterior cingulate gyrus; CRN, correct-response negativity; CSd, dorsal segment of central sulcus; DLPFC, dorsolateral prefrontal cortex; ERN, error-related negativity; ERP, event-related potential; fMRI, functional magnetic resonance imaging; IFJ, inferior frontal junction; IPL, inferior parietal lobe; IPS, intraparietal sulcus; IQ, intelligence quotient; MCC, midcingulate cortex; MARS, math anxiety rating scale; NAc, nucleus accumbens; Pe, error-related positivity; SEMA, scale for early mathematics anxiety; tDCS, transcranial direct current stimulation; VMPFC, ventromedial prefrontal cortex.

Regarding the fear network, high math-anxious children showed hyperactivity and abnormal effective connectivity in the right basolateral amygdala (Young et al., 2012). Since the amygdala is known for fear perception, its activation during a math task confirms the children's fear of math. Moreover, the aberrant connectivity of the amygdala is reflected by a greater connectivity to the ventromedial prefrontal cortex in order to facilitate compensatory mechanisms for performance and by a reduced connectivity to the bilateral superior parietal lobule, leading to the performance deficit.

In summary, the affective component of math anxiety is associated with pain-related activity before math tasks and fear-related activity during math tasks, independent of trait anxiety. However, are both networks active in the same math-anxious individual or is this age-dependent? Since evidence for pain-related activity was found in adults and evidence for fear-related activity was found in children, the data point to an age-dependency of recruited networks which should be systematically studied with the same paradigms.

Emotion Regulation in Math Anxiety

Since math anxiety elicits negative emotional responses to math, high math-anxious individuals need to process and regulate these emotions which lead to cognitive consequences (Rubinsten and Tannock, 2010). Consequently, working memory is occupied with the math-related anxiety and less resources are available for the math task, resulting in impaired math performance (Ashcraft and Kirk, 2001, Ashcraft and Krause, 2007). The detrimental effect of math anxiety on performance is mediated by working memory and emotion regulation (Hopko et al., 1998; Ashcraft and Krause, 2007).

On the neural level, brain connectivity and brain activity patterns are altered by math anxiety due to emotion regulation. For instance, high math-anxious children showed a greater coupling of the hyperactive amygdala with cortical regions involved in processing and regulating negative emotions during the math task (Young et al., 2012). This led to greater deactivation in the ventromedial prefrontal cortex compared to their low math-anxious counterparts. Furthermore, the typical neural activation within the left inferior frontal gyrus and the insula for the processes of place-value integration in multi-digit numbers was absent in high math-anxious individuals (Pletzer et al., 2015). These areas are associated with inhibitory control during the number comparison task. The results, therefore, suggest that math anxiety inhibits emotional processing within task-irrelevant areas instead of activating task-relevant inhibitory control regions (Pletzer et al., 2015). Thus, math-anxious individuals seemingly focus on their math-related emotions during the task rather than on the task itself which can be detrimental for their task performance. However, the neuroscientific literature does not hint at the strategies involved in emotion regulation (cf. Gross and John, 2003).

Controlling math-related emotions in math-anxious individuals does not automatically result in performance impairment. Emotion regulation can even help prevent or at least minimize the impact of an anxiety-caused performance deficit. Lyons and Beilock (2012a) observed that high math-anxious individuals who used the fronto-parietal network associated with cognitive control and emotion regulation before the math task, compensated for their math-related deficit. This network, consisting of the bilateral inferior frontal junction and the bilateral inferior parietal lobe, is associated with high-level cognitive control processes. When high math-anxious individuals ramp up these resources before the math task starts, activation in the right nucleus accumbens and the left hippocampus, associated with motivating behavior, and integration of cognitive control, is increased during math performance. (Lyons and Beilock, 2012a; Young et al., 2012). Consequently, they show almost no math deficit despite their math anxiety.

The dorsolateral prefrontal cortex (DLPFC), as one part of this fronto-parietal network (Lyons and Beilock, 2012a), seems critical for the math anxiety-induced mediation of emotion regulation on math performance. When performance in the math task was not controlled for, high math-anxious individuals showed reduced activity in the right DLPFC and the bilateral basal ganglia associated with working memory and attention (Young et al., 2012). When performance was controlled for, the response to the compatibility effect was reduced in the left DLPFC (Pletzer et al., 2015). When processing in the DLPFC was enhanced by applying transcranial direct current stimulation (tDCS), high math-anxious individuals showed improved performance in a simple arithmetic task and less stress during the math task as indicated by decreased cortisol concentrations (Sarkar et al., 2014). Interestingly, the same stimulation protocol had the opposite effect on individuals with low math anxiety – arithmetic performance was impaired and cortisol decrease was prevented. Taken together, math anxiety is associated with reduced DLPFC activity independent of math performance, but by facilitating processing within the DLPFC, the negative emotional reaction to math can be reduced and thus math performance improves.

To sum up, math anxiety elicits a negative emotional response to the math task, usually leading to impaired performance because of the additional involvement in emotion regulation. However, by enhancing the capacity for emotion regulation or cognitive control, high math-anxious individuals can compensate for their math-specific performance deficit. This influence of math anxiety on performance in arithmetic tasks can be conceptualized in a more general theoretical framework addressing the impact of anxiety on processing efficiency.

Impact of Math Anxiety on Processing Efficiency

Anxiety is hypothesized to have a general influence on processing efficiency (cf. processing efficiency theory, Eysenck and Calvo, 1992; and its extension: attentional control theory, Eysenck et al., 2007). Performance efficiency is the relationship between performance effectiveness (the quality of performance) and processing efficiency (the use of processing resources). According to both theories, "anxiety impairs processing efficiency more than performance effectiveness" though "impairing the efficiency of the central executive component of the working memory system" (Derakshan and Eysenck, 2009). In the attentional control theory (where attentional control refers to an individual's capacity to choose what to pay attention to), it is assumed that anxiety impairs both positive and negative attentional control. Attentional and processing resources are diminished by worry, and compensated by increased cognitive efforts. ERP studies (Suárez-Pellicioni et al., 2013a,b, 2014) and a neuro-imaging study (Pletzer et al., 2015) suggest that the processing efficiency hypothesis mentioned above can be applied to math anxiety and its relation to arithmetic performance.

First, it was shown that math anxiety influenced simple arithmetic within a verification task, although math ability and general anxiety were controlled for (Suárez-Pellicioni et al., 2013a). When the solution of the single-digit addition problem was dramatically incorrect and had to be rejected, the evoked P600/3b component was enhanced and delayed with increasing math anxiety. Thus, high math-anxious individuals have problems with inhibiting distractor-related processing and, therefore, need more resources and time to evaluate such solutions, i.e., math anxiety decreases processing efficiency in simple arithmetic tasks which is in line with the processing efficiency theory.

Second, math anxiety led to abnormal conflict monitoring and adaptation within a numerical Stroop task (Suárez-Pellicioni et al., 2013b, 2014). For instance, during the evaluation of errors, the error-related negativity (response-locked potential at 50–150 ms after the occurrence of an error) was enhanced, with no difference in behavioral performance (Suárez-Pellicioni et al., 2013b). This suggests that high math-anxious individuals have to increase their cognitive effort to compensate for fewer resources. Furthermore, math anxiety causes abnormal conflict adaptation: the early N450 potential is missing during conflict processing and subsequently the sustained conflict potential is increased, suggesting a rise of cognitive control to solve the conflict (Suárez-Pellicioni et al., 2014). Therefore, math anxiety is associated with a reactive recruitment of attentional control and increased distractibility to task-irrelevant information. This supports the attentional control theory, since anxiety is considered to reduce attentional resources to the task and thus cognitive effort has to be increased in order to reach comparable performance. Moreover, independent of general anxiety, it shows the specific effect of math anxiety on processing efficiency.

Finally, math anxiety reduced the deactivation of the default mode network which usually shows less activation during cognitive tasks (Pletzer et al., 2015). In particular, a moderately stronger deactivation within the task-related default mode network including the precuneus and the anterior cingulate gyrus was found in low compared to high math-anxious individuals. Since deactivation of the default mode network is an indicator of processing efficiency, math anxiety reduces processing efficiency in the math task and increases the effort to control the negative emotional response in order to achieve similar performance.

The neuroscientific findings support the idea that the processing efficiency theory can be applied to math anxiety. High math-anxious individuals show less efficient neural processing in numerical tasks and thus require more effort than low-anxious individuals to reach similar performance levels.

Math Anxiety and Math Performance Deficit

Math anxiety considerably impacts performance in math tasks (Ma, 1999; Ashcraft and Kirk, 2001; Cates and Rhymer, 2003; Ashcraft and Moore, 2009). Several behavioral studies suggest that math anxiety especially impairs performance in difficult math tasks, as indicated by the anxiety–complexity effect (Ashcraft and Faust, 1994; Faust et al., 1996; Ashcraft and Kirk, 2001; Suárez-Pellicioni et al., 2013a). This implies that the more complex the arithmetic problem, the larger the impairment of the high math-anxious individuals. For instance, the detrimental effect of math anxiety on performance in an arithmetic task is larger for two-digit than for single-digit addition or for addition requiring a carry operation compared to addition not requiring a carry operation (Faust et al., 1996). However, more recent behavioral (Maloney et al., 2010, 2011) and ERP studies (Suárez-Pellicioni et al., 2013a; Núñez-Peña and Suárez-Pellicioni, 2014) provide evidence that math anxiety already affects basic number processing: number magnitude processing, place-value processing and simple arithmetic processing.

Essentially, high math-anxious individuals have a less precise number magnitude representation than their low math-anxious counterparts (Núñez-Peña and Suárez-Pellicioni, 2014). This was found in a symbolic number comparison task for both the distance and the size effect, reflected by increased amplitude of the positive peak in the difference wave around 200–250 ms and corroborated by increased reaction time differences on the behavioral level. This shows that already the underlying mechanisms of basic numerical processing are altered by math anxiety.

Math anxiety furthermore influences place-value processing within a number comparison task. Thus, the compatibility effect was accompanied by higher neural activation in the inferior frontal cortex in incompatible trials for low math-anxious individuals but not for high math-anxious individuals (Pletzer et al., 2015). The finding suggests a math anxiety-related failure when inhibitory functions related to the numerical stimuli are required and thus, basic place-value integration is not effective. This goes beyond behavioral studies on complex place-value integration such as the carry effect (Faust et al., 1996).

The neurocognitive effect of math anxiety on performance in simple arithmetic has already been shown in children (Young et al., 2012). Compared to their low math-anxious counterparts, high math-anxious children show less activation in the left intraparietal sulcus, superior parietal lobe and right DLPFC, i.e., in the fronto-parietal network responsible for numerical processing. This underactivation within the number processing network causes their math anxiety-related deficit in performance, reflected by marginally lower accuracy and less differentiation between RTs across difficulty levels. While the authors assume the neural effect to be independent of performance, this activation pattern could not be replicated in other studies (Lyons and Beilock, 2012a,b; Pletzer et al., 2015) and thus further research has to disentangle the confound of math anxiety and performance.

In conclusion, math anxiety affects the neural signatures of basic numerical effects, even when performance in the respective tasks is comparable. This shows that math anxiety not only hinders mathematical learning, causing a math deficit which can be observed in more complex math tasks, but also that the emotional response to math already alters basic number processing on a neural level. However, further research is needed to neurocognitively evaluate the impact of math anxiety on task difficulty.

Conclusion and Perspectives

Neurocognitive studies suggest that math anxiety elicits an affective response within the fear and pain network in the brain. In order to deal with these negative emotions, brain areas associated with emotion regulation are active during math performance which may lead to limited capacities, impaired performance, and less efficient processing even in simple tasks. However, by extending these cognitive and emotional control capacities within the fronto-parietal brain network, high math-anxious individuals may still be able to compensate for the anxiety-related performance deficit. The neuroscientific literature suggests interventions which focus on controlling the negative emotional response to math (Lyons and Beilock, 2012a) to overcome the vicious circle of math anxiety and poor math performance.

The most important problem for research on math anxiety is that the neurocognitive activation patterns for math anxiety are confounded with math performance, since high math-anxious individuals usually perform worse in math tasks than their low anxious counterparts. When performance is not controlled for, the resulting effects of math anxiety could be due to this performance difference rather than due to math anxiety. Future research should, therefore, disentangle this confound by differentiating the math anxiety groups matched for math ability (cf. Pletzer et al., 2015) or using the interindividual variability in performance within the high math-anxious group (cf. Lyons and Beilock, 2012a). Note that the simple use of covariates may not be appropriate when relations between math anxiety and other variables are not linear.

Investigating the neurocognitive foundations of math anxiety can help explain the mechanisms that lead to performance deficits, detect anxiety-related differences in brain function, also in the absence of behavioral differences, and identify physiological markers of the emotional response to math. However, the few studies focusing on the neural correlates of math anxiety vary greatly in their methods (neuro-imaging, neurophysiological, and non-invasive brain stimulation), tasks (from simple numerical to complex arithmetic), and samples (adults, children). The methods differ in the investigation of correlational and causal structure–function relationships, the complexity of numerical tasks determines the degree of involvement of working memory resources and math ability levels depend on development. This leads to highly inconsistent results with little overlap between studies (cf. **Figure 1**). So far, this can be explained by differences in assessment, paradigms, and samples. Future research may address these issues by systematically manipulating methods, tasks, and samples to ensure that different results in different studies are due to methodological differences. Research on developmental trajectories could especially help identify the age-related neurocognitive correlates of math anxiety.

Acknowledgments

All authors are members of the LEAD Graduate School (GSC1028) funded by the Excellence Initiative of the German federal and state governments. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of University of Tuebingen.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 27 October 2015
doi: 10.3389/fpsyg.2015.01621

The influence of math anxiety on symbolic and non-symbolic magnitude processing

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Deficits in basic numerical abilities have been investigated repeatedly as potential risk factors of math anxiety. Previous research suggested that also a deficient approximate number system (ANS), which is discussed as being the foundation for later math abilities, underlies math anxiety. However, these studies examined this hypothesis by investigating ANS acuity using a symbolic number comparison task. Recent evidence questions the view that ANS acuity can be assessed using a symbolic number comparison task. To investigate whether there is an association between math anxiety and ANS acuity, we employed both a symbolic number comparison task and a non-symbolic dot comparison task, which is currently the standard task to assess ANS acuity. We replicated previous findings regarding the association between math anxiety and the symbolic distance effect for response times. High math anxious individuals showed a larger distance effect than less math anxious individuals. However, our results revealed no association between math anxiety and ANS acuity assessed using a non-symbolic dot comparison task. Thus, our results did not provide evidence for the hypothesis that a deficient ANS underlies math anxiety. Therefore, we propose that a deficient ANS does not constitute a risk factor for the development of math anxiety. Moreover, our results suggest that previous interpretations regarding the interaction of math anxiety and the symbolic distance effect have to be updated. We suggest that impaired number comparison processes in high math anxious individuals might account for the results rather than deficient ANS representations. Finally, impaired number comparison processes might constitute a risk factor for the development of math anxiety. Implications for current models regarding the origins of math anxiety are discussed.

Keywords: math anxiety, approximate number system, magnitude representation, symbolic, non-symbolic

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *25 June 2015*
Accepted: *07 October 2015*
Published: *27 October 2015*

Citation:
Dietrich JF, Huber S, Moeller K and Klein E (2015) The influence of math anxiety on symbolic and non-symbolic magnitude processing. Front. Psychol. 6:1621. doi: 10.3389/fpsyg.2015.01621

INTRODUCTION

Mathematics anxiety has been defined as feelings of tension, apprehension, or fear which interfere with math performance in various contexts such as school but also everyday and professional life (e.g., Richardson and Suinn, 1972; Ashcraft, 2002). Thus, negative consequences of math anxiety are serious and far-reaching. On the psychological level, math anxiety was found to be associated with reduced motivation for math and lower self-concept as regards math (Hembree, 1990). On the behavioral level, math anxiety was related to a tendency to avoid mathematics (Hembree, 1990). Additionally, math anxiety was also found to be associated negatively with math performance (see Hembree, 1990; Ma, 1999, for meta-analyses). This latter point is particularly worrying, because numerical abilities are key competences in our society today, which predict individual scholastic and professional prospects (Bynner and Parsons, 2006; Hudson et al., 2009). Due to this wide range of negative effects associated with math anxiety, it is important to understand the factors leading to the development of math anxiety.

Currently, there are several approaches accounting for the development of mathematics anxiety (e.g., see Maloney and Beilock, 2012, for a review). The most comprehensive model by Ashcraft et al. (2007) postulates three risk factors for the development of math anxiety: (1) inadequate math skills, (2) insufficient motivation, or (3) poor working memory. All these three factors can lead to deficits in math performance which increase the probability of developing math anxiety (see also Ashcraft and Moore, 2009 for a detailed description of the model). In combination with negative learning experiences (e.g., negative feedback of teachers and parents) these risk factors may also lead to negative attitudes toward math and increase self-focused attention and rumination, which in turn may contribute to the development of math anxiety.

Ashcraft and Moore (2009) proposed that the risk factor ‘inadequate math skills’ may also include deficits in basic numerical competencies such as counting or number knowledge. In line with this, Maloney et al. (2010) found that high math anxious individuals indeed presented with deficient counting abilities. Moreover, Maloney et al. (2011) proposed that a deficient representation of numerical magnitude (i.e., a deficient approximate number system; ANS) might contribute to the development of math anxiety (see also Núñez-Peña and Suárez-Pellicioni, 2014). The ANS is assumed to represent numerical magnitude information (i.e., numerosity) in an approximate manner (e.g., Cantlon et al., 2009). In particular, it was suggested that numerosities are represented in the ANS by overlapping Gaussian tuning curves. These tuning curves reflect the activity of neurons showing a maximum neural activation for a specific magnitude and an attenuated activation for adjacent magnitudes (e.g., see Feigenson et al., 2004, for a review). Importantly, the ANS was proposed to constitute a building block for later more complex numerical/mathematical abilities (Dehaene, 2001). In line with this, ANS acuity was found to predict later math performance (e.g., Mazzocco et al., 2011; Libertus et al., 2013).

Supporting the idea of math anxiety being caused by a deficient ANS, Maloney et al. (2011) found a larger distance effect for high math anxious individuals than for low math anxious individuals (see Núñez-Peña and Suárez-Pellicioni, 2014, for similar results). The distance effect describes the finding that response time (RT) and error rates (ERs) increase as the numerical distance between two to-be-compared numbers decreases (Moyer and Landauer, 1967). For instance, participants’ RTs and ERs are larger when comparing 3 vs. 4 than when comparing 2 vs. 8. This effect can be explained by a larger overlap of the ANS representations for less distant magnitudes according to ANS theory (e.g., Dehaene et al., 1998). Additionally, Núñez-Peña and Suárez-Pellicioni (2014) observed a marginal significant interaction between the size effect and math anxiety. In their study, high math anxious participants showed a larger size effect than low math anxious participants. The size effect refers to the observation that the processing of numbers becomes more difficult as the size of the numbers to be processed increases (see Zbrodoff and Logan, 2005, for a review). Also the size effect can be explained by ANS theory (e.g., Dehaene et al., 1998). It is assumed that the overlap between the ANS representations increases with numerosity (Feigenson et al., 2004). Thus, it should be more difficult to discriminate between larger magnitudes (e.g., 8 vs. 9) than between smaller magnitudes (e.g., 1 vs. 2; i.e., the size effect, e.g., Parkman, 1971).

Both studies assessed ANS acuity using a symbolic Arabic number comparison task (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014). However, this procedure was based on the common assumption that magnitude representations in the ANS are abstract, this means modality independent (e.g., Libertus et al., 2007; Piazza et al., 2007). Hence, the ANS may be assessed using either Arabic number symbols or non-symbolic stimuli such as dot patterns. However, there is accumulating evidence questioning the notion of an abstract, modality-independent magnitude representation (see Cohen Kadosh and Walsh, 2009 for a review). Only recently, for example, Bulthé et al. (2014) found no representational overlap for symbolic and non-symbolic magnitudes. Moreover, Lyons et al. (2015) showed that symbolic and non-symbolic magnitudes are coded fundamentally differently. These recent results question the assumption that ANS acuity may be measured validly using a symbolic number comparison task. This in turn challenges the conclusion of Maloney et al. (2011; see also Núñez-Peña and Suárez-Pellicioni, 2014) that the association between math anxiety and the symbolic distance effect found in previous studies should be driven by a deficient ANS.

Moreover, it was also questioned recently whether the distance and/or the size effect – derived from a symbolic number magnitude comparison task – are valid indices of ANS acuity (e.g., Verguts et al., 2005; Van Opstal et al., 2008). For instance, Van Opstal et al. (2008) observed that the distance effect measured in a symbolic number magnitude comparison task does not necessarily imply an overlap of the magnitude representations of individual numbers as suggested by the ANS theory. Instead, the distance effect might be driven by response-related processes. Furthermore, Verguts et al. (2005) provided an alternative explanation for the size effect. In a computational modeling study, they showed that the size effect depended on the differential frequency of the individual numbers during learning (i.e., the lower frequency of larger numbers). In line with this result, Dehaene and Mehler (1992) found that the frequency of numbers in daily life decreased with increasing numerical magnitude, which might cause the size effect. These alternative explanations for the distance and size effect further question the conclusions of previous studies that modulations of the distance effect and the size effect by math anxiety are associated with

ANS acuity, because both effects may not necessarily reflect ANS acuity.

Hence, in the present study, we examined whether ANS acuity is indeed related to math anxiety and, consequently, may represent a risk factor for the development of math anxiety. To do so, we employed the current standard task to assess ANS acuity: the non-symbolic dot comparison task (see De Smedt et al., 2013; Dietrich et al., 2015, for reviews). Recently, there has been an increasing amount of research concentrating on cognitive processes involved in the solution process of a dot comparison task (e.g., inhibitory control, Gilmore et al., 2013) and methodological factors influencing task performance. For instance, task performance was found to be influenced by visual stimulus parameters (e.g., Szűcs et al., 2013), presentation duration (Inglis and Gilmore, 2013) and set size (Clayton and Gilmore, 2015; see Dietrich et al., 2015, for a detailed discussion about the reliability/validity of ANS tasks as well as methodological aspects relevant for the design of an ANS task). Therefore, we designed the non-symbolic dot comparison task considering these methodological aspects in order to assess ANS acuity as reliably and as validly as possible. Moreover, several measures were used to index ANS acuity. However, recent studies question the assumption that all indices can be used interchangeably, although this issue is not fully resolved yet (Lindskog et al., 2013; Inglis and Gilmore, 2014). To account for this methodological issue we considered several indices to reflect ANS acuity: ER, mean RT, the distance, the size effect as well as the Weber fraction. The latter is assumed to be the most direct index of ANS acuity (reflecting the width of the Gaussian tuning curves, i.e., the precision of the ANS representations; Pica et al., 2004). If a deficient ANS indeed underlies math anxiety, this should be reflected by a reliable association of math anxiety and these measures. However, a significant correlation might be present not for all measures, because previous research found considerable differences regarding the reliability of these measures (Lindskog et al., 2013; Inglis and Gilmore, 2014). To allow for a direct comparison of our results with previous findings, we also administered a symbolic number comparison task. We expected to replicate the findings of Maloney et al. (2011) and Núñez-Peña and Suárez-Pellicioni (2014) who found a (marginally) significant positive association between math anxiety and the distance and the size effect for RTs in the symbolic number magnitude comparison task.

MATERIALS AND METHODS

Participants

Sixty-one undergraduates (37 female, 3 left-handed, mean age = 24.7 years, $SD = 3.3$ years) participated in the experiment. All participants were informed about the experimental procedure before they provided written consent to participate. Participation was compensated with 8€ per hour. The study was approved by the local ethics committee of the Leibniz-Institut für Wissensmedien.

Materials

The Abbreviated Math Anxiety Scale (AMAS)

The AMAS is a nine-item scale to assess math anxiety. Participants are asked to indicate on a 5-point Likert scale from 1 (low anxiety) to 5 (high anxiety) how anxious they feel in various math-related situations. Adequate internal consistency (Cronbach's $\alpha = 0.90$), test-retest reliability ($r = 0.85$) and construct validity have been reported for this instrument (Hopko et al., 2003). In the current study the internal consistency of the AMAS was similar to the results of Hopko et al. (2003; Cronbach's $\alpha = 0.92$). The AMAS score was calculated by adding up participants responses on the Likert scales.

Symbolic Number Comparison

In the symbolic number comparison task, two single digits were presented simultaneously, one above the other on a 19 inch monitor with a resolution of 1024 pixel × 768 pixel and 75 Hz. Participants had to single out the larger of the two digits. When the upper digit was the larger one, they should press the "Z" key on a standard QWERTZ keyboard with their right index finger. When the lower digit was the larger one, they should press the "B" key with their left index finger. The digits remained visible on the screen until the participants pressed one of the response buttons. Each number pair was preceded by a fixation point, which was presented for 500 ms. All possible combinations of the single digits 1 to 9 (i.e., 72 different digits pairs) were presented five times resulting in a total of 360 experimental trials. Participants completed five practice trials before the experimental trials started. Digits were presented using font "Courier New" with font size set to 60 at the x/y coordinates 512/484 and 512/284. The internal consistency of the symbolic number comparison task was Cronbach's $\alpha = 0.92$ and Spearman-Brown corrected split-half reliability was $r = 0.87$.

Non-symbolic Dot Comparison

In the non-symbolic dot comparison task, two dot sets were presented simultaneously – one set on the left and one set on the right side of the screen. Both sets were separated by a black vertical line. Participants were instructed to indicate, which of the two sets contained more dots, by pressing the corresponding key (i.e., press the left Ctrl key when the left set is larger or the right Ctrl key when the right set is larger). Position of the larger dot set was counterbalanced across screen sides. Dot sets included black dots against a white background and were presented on the screen for 200 ms. Afterward a white screen was presented, which remained visible until participants pressed one of the response keys. Each trial started with a fixation sign (i.e., a black square) displayed for 500 ms. Dot sets contained between 10 and 40 dots. The ratios between the two to-be compared dot sets were 0.5, 0.6, 0.7, 0.8, and 0.9. There were 80 trials per ratio resulting in a total of 400 experimental trials. Before the experimental trials started, five practice trials were presented. To control for visual properties, dot sets were created with the MATLAB script of Gebuis and Reynvoet (2011). In half of the trials convex hull (i.e., area in which the dots can appear) and item size (i.e., average diameter of the dots in one set) were larger for the more numerous set, whereas in the other half of the trials, convex hull and item size were smaller for the more numerous set. The internal consistency of the non-symbolic dot comparison task was Cronbach's $\alpha = 0.96$ and Spearman-Brown corrected split-half reliability was $r = 0.91$.

Procedures

All participants were tested individually. First, they had to complete the AMAS followed by the magnitude comparison tasks. The order of the symbolic number comparison task and the non-symbolic dot comparison task was counterbalanced across participants.

Analysis

We analyzed RTs as well as ERs. We included all responses in the analysis of RTs (correct and incorrect responses). This procedure was chosen, because in the non-symbolic comparison task the percentage of errors was quite high, which would have reduced the number of observations considerably. However, the same analyses including only RTs of correct responses did yield the same pattern of results. A trimming procedure excluded RTs deviating more than 3 *SD* from the individual mean. This outlier analysis reduced the data set of the symbolic number comparison task by 1.63% and the data set of the non-symbolic dot comparison task by 1.77%.

Response times were analyzed using linear mixed effects models (LME). For the analysis of ER, generalized linear mixed effects models (GLME) with a binomial error distribution and the logit as link function were employed. All statistical analysis were run using R (R Core Team, 2015) and the R package lme4 for the (G)LME (Bates et al., 2014). The *p*-values for LME were calculated using the Satterthwaite approximation for degrees of freedom available via the R package lmerTest (Kuznetsova et al., 2015). The *p*-values for GLME were derived via likelihood ratio tests using the R package afex (Singmann et al., 2015).

Fixed effects in our analyses (LME and GLME) were distance (i.e., the distance between the to-be-compared numbers/numerosities), size (i.e., the sum of the two numbers/dots in both sets), the AMAS score and the interaction between distance and AMAS score as well as between size and AMAS score. The predictors distance and size were z-transformed prior to data analysis and the AMAS score was centered.

In line with the suggestion of Barr et al. (2013), we first attempted to fit the LME for RT data using the maximum random effects structure. Thus, we included the fixed effects distance and size also as random effects as well as a random intercept for participants in the analysis of the symbolic and the non-symbolic comparison task and a random intercept for items in the analysis of the non-symbolic comparison task. In the GLME (ER data) for the symbolic comparison task, we included a random intercept for participants. In the GLME (ER data) for the non-symbolic comparison task, we also included a random intercept for items to account for the fact that we included only a sample of all possible items.

Additionally, we estimated the Weber fraction indicating the acuity of the ANS representation using the following formula (Pica et al., 2004):

$$f_{acc}(r, w) = 1 - \frac{1}{2} erfc\left(\frac{|r-1|}{\sqrt{2}w\sqrt{r^2+1}}\right)$$

The formula describes the probability f_{acc} of correctly comparing two numerosities with a given ratio r (i.e., the ratio between the larger and the smaller numerosity) for a participant with an internal Weber fraction w using the complementary Gauss error function erfc. Individual Weber fractions were fitted using the Gauss–Newton algorithm for non-linear least squares fit on the mean accuracy for each ratio and the R package pracma for the erfc function (Borchers, 2015). For eight participants, the fitting function did not converge or the Weber fraction was not a reliable predictor of mean accuracy of participants. Thus, we included 53 participants in the analysis containing the Weber fraction. To investigate, whether math anxiety is related to ANS acuity indexed by the Weber fraction we conducted a linear regression analysis with AMAS score as dependent variable and the individual Weber fraction as independent variable. Null effects were validated using a Bayesian model selection approach, which investigates whether the null hypothesis or the alternative hypothesis is more supported by the data (Masson, 2011). We calculated the posterior probability that the data favor the null hypothesis and the complement that the data favor the alternative hypothesis. According to the classification of Raftery (1995) a posterior probability of >0.75 provides positive evidence in favor of the investigated hypothesis.

RESULTS

An overview of the descriptive statistics of the variables is given in **Table 1**. Additionally, **Table 2** shows the relationships between all these variables.

TABLE 1 | Mean, standard deviation (*SD*) and range of all variables.

Variable	Mean	*SD*	Minimum	Maximum
Abbreviated Math Anxiety Scale (AMAS) score	22.03	8.11	10	39
ER symbolic comparison task	3.82%	2.95%	0.28%	16.94%
ER non-symbolic comparison task	32.92%	9.02%	17.25%	50.75%
RT symbolic comparison task	664.75 ms	80.64 ms	514.45 ms	899.44 ms
RT non-symbolic comparison task	681.87 ms	199.22 ms	304.52 ms	1278.52 ms
Weber fraction	0.60	0.40	0.24	2.74

Higher AMAS scores reflect higher math anxiety and vice versa. Smaller Weber fractions reflect a more precise ANS. ER, error rate; RT, response time.

TABLE 2 | Spearman correlation coefficients between all variables.

	(1)	(2)	(3)	(4)	(5)	(6)
(1) AMAS score	1					
(2) ER symbolic comparison task	−0.10	1				
(3) RT symbolic comparison task	0.16	−0.53***	1			
(4) ER non-symbolic comparison task	0.11	0.13	0.16	1		
(5) RT non-symbolic comparison task	−0.10	−0.37*	0.39*	−0.38*	1	
(6) Weber fraction	0.09	0.13	0.18	0.99***	−0.36*	1

*$p < 0.05$, ***$p < 0.001$; p-values were adjusted for multiple testing using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995). ER, error rate; RT, response time; AMAS, Abbreviated Math Anxiety Scale.*

Response Times

First, we investigated separately for the symbolic and the non-symbolic comparison task whether math anxiety (reflected by the AMAS score) influences overall RT as well as the distance and the size effect for RT. A possible influence of math anxiety on overall RT would be indicated by a significant main effect of the AMAS score. Furthermore, an influence of math anxiety on distance or size effects for RT would be reflected by a significant interaction between AMAS score and distance or size. The results of the LME for RT data are given in **Table 3**, both for the symbolic number comparison task and the non-symbolic dot comparison task. We observed reliable effects of numerical distance and size for both tasks. For the symbolic comparison task, RT decreased with numerical distance between the two digits and increased with their numerical size. Similarly, the significant distance effect in the non-symbolic dot comparison task indicated that participants' RT decreased with numerical distance between the two dot sets. However, in contrast to the symbolic comparison task, we found that RT decreased with numerical size for the non-symbolic dot comparison task. Importantly, we observed a reliable interaction between AMAS score and distance in the symbolic comparison task. As shown in **Figures 1** and **2**, the interaction indicated that participants with a higher AMAS score showed a larger distance effect than participants with a lower AMAS score. However, we did not find a significant interaction between AMAS score and distance in the non-symbolic dot comparison task. For both, the symbolic and the non-symbolic task there was no significant interaction between size and AMAS score. Moreover, there was also no reliable effect of the AMAS score on RT. An analog analysis with a categorical predictor (i.e., low vs. high math anxious group) instead of a continuous predictor for the AMAS score revealed an identical pattern of results (see Table A1 in the Supplemental Material).

Error Rates

Second, similar to the analysis for RT, we investigated the influence of math anxiety (i.e., AMAS score) on overall performance as well as distance and size effects based on ERs. Again, an influence of math anxiety would be indicated by either a significant main effect of AMAS score or a reliable interaction between AMAS score and distance or size. The results for ER data are summarized in **Table 4**. In line with the results for RT, we found reliable distance and size effects for both tasks. For the symbolic task, we observed that ER decreased as the numerical distance between the numbers increased (log odds = −0.349; in %: −0.64%), whereas they increased with the size of the numbers (log odds = 0.148; in %: 0.34%). The same pattern was observed for the non-symbolic task. ER also decreased with the numerical distance between dot sets (log odds = −0.070; in %: −1.45%) and increased with their size (log odds = 0.009; in %: 0.18%). There were no significant interactions between the AMAS score and distance or size neither in the symbolic nor in the non-symbolic task. Hence, we could not find an analog pattern for ER as for RT, where we found a significant interaction between the AMAS score and the distance effect for the symbolic comparison task. The missing interaction for ER might be explained by a ceiling effect for the symbolic comparison task. The ERs were very low, which might have reduced the variance and, hence, the effect. Moreover, there was no significant effect of the AMAS score on ER. An analog analysis with a categorical predictor for the AMAS score revealed an identical pattern of results (see Table A2 in the Supplemental Material).

Weber Fraction

Finally, we investigated whether the Weber fraction, which is assumed to be the most direct measure of ANS acuity, was related to the individual AMAS score. A linear regression analysis predicting AMAS score from individual Weber fraction revealed no significant effect [$B = 3.119$, $\beta = 0.148$, $t(51) = 1.07$, $p = 0.292$]. Moreover, the model accounted for only 2.18% of the variance in AMAS score [$F(1,51) = 1.14$, $p = 0.292$]. This null effect was further investigated using a Bayesian model selection approach. The posterior probability for the null hypothesis was 0.80 providing positive evidence for the null hypothesis (i.e., no relationship between AMAS score and Weber fraction) according to Raftery (1995).

DISCUSSION

In the present study, we investigated whether ANS acuity is related to math anxiety and may, therefore, constitute a risk factor for the development of math anxiety. Complementing previous studies (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014) we used not only a symbolic number comparison task but also a non-symbolic dot comparison task to assess ANS acuity. Additionally, we employed not only the distance and the size effect as indices of ANS acuity, but also evaluated ER, mean RT, and the Weber fraction. The latter is assumed to reflect the precision of the ANS representations directly (e.g., Pica et al., 2004). We replicated the significant association between math anxiety and the distance effect based on RT for the symbolic number comparison task. However, we did not observe an association of size effect and math anxiety. Furthermore, we did not observe a relationship between math anxiety and any of the ANS measures based on the non-symbolic dot comparison task.

TABLE 3 | Estimates of fixed effects (ms) for response times.

Task	Effect	Estimate (*SE*)	df	*t*	*p*	95% CI
Symbolic comparison	Intercept	665.063 (10.07)	61.00	66.03	<0.001	[645.32, 684.80]
	Distance	−16.111 (0.75)	60.99	−21.36	<0.001	[−17.59, −14.63]
	AMAS	1.848 (1.25)	61.00	1.48	0.145	[−0.61, 4.30]
	Size	4.157 (0.44)	60.90	9.52	<0.001	[3.30, 5.01]
	Distance × AMAS	−0.230 (0.09)	60.99	−2.46	0.017	[−0.41, −0.05]
	Size × AMAS	0.040 (0.05)	60.85	0.74	0.461	[−0.07, 0.15]
Non-symbolic comparison	Intercept	682.048 (25.28)	61.35	26.99	<0.001	[632.51, 731.59]
	Distance	−1.876 (0.57)	93.23	−3.28	0.001	[−3.00, −0.75]
	AMAS	−1.880 (3.14)	61.00	−0.60	0.551	[−8.03, 4.27]
	Size	−1.117 (0.22)	98.06	−5.13	<0.001	[−1.54, −0.69]
	Distance × AMAS	−0.056 (0.06)	60.79	−0.88	0.380	[−0.18, 0.07]
	Size × AMAS	−0.004 (0.02)	60.85	−0.18	0.859	[−0.05, 0.04]

95% CI based on the estimated local curvature of the likelihood surface.

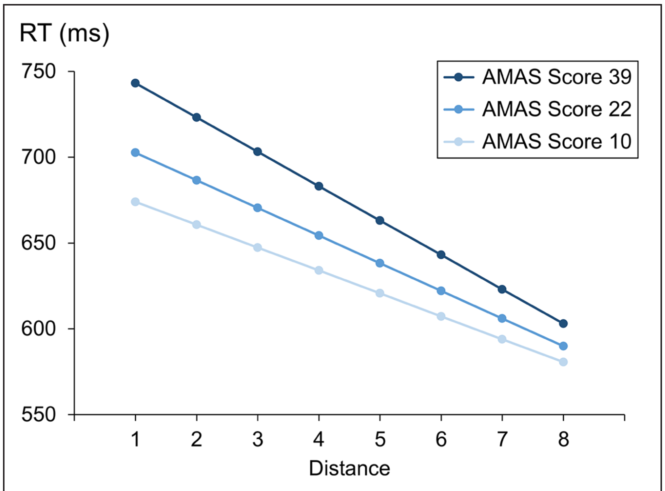

FIGURE 1 | Illustration of the estimated distance effects for participants with low math anxiety [Abbreviated Math Anxiety Scale (AMAS) score = 10, the smallest AMAS score in our sample], middle math anxiety (AMAS score = 22, mean of AMAS scores in our sample) and high math anxiety (AMAS score = 39, the largest AMAS score in our sample).

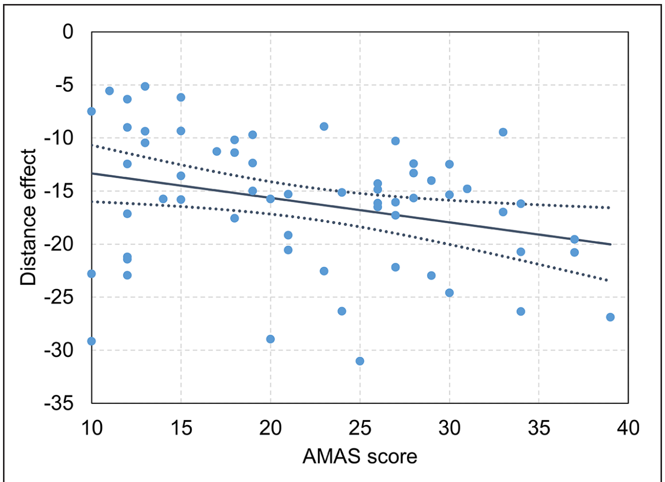

FIGURE 2 | Relationship between symbolic distance effect for response times (RTs) and Abbreviated Math Anxiety Scale (AMAS) score. Dark blue line reflects slope of the interaction between distance effect and AMAS score, dotted dark blue lines indicates 95% CI, dots reflect individual distance effects and AMAS scores. Higher AMAS scores reflect higher math anxiety and vice versa.

In the following, we will first discuss the implications of these results for the proposed association of ANS acuity and math anxiety before elaborating conclusions for symbolic number processing and math anxiety and theoretical implications for models on the origins of math anxiety.

ANS Acuity and Math Anxiety

Recently, it was suggested that a less precise ANS might contribute to the development of math anxiety (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014). These studies, however, did not measure ANS acuity using a non-symbolic dot comparison task, which represents the standard task to assess ANS acuity (e.g., Halberda et al., 2008; De Smedt et al., 2013; Gilmore et al., 2014; Inglis and Gilmore, 2014; Dietrich et al., 2015), but used a symbolic number comparison task instead. The use of the symbolic number comparison task to assess ANS acuity is valid when assuming that numerical magnitudes are represented in the ANS in an abstract, modality-independent manner. In this case only ANS acuity can be assessed using either symbolic or non-symbolic magnitude comparison tasks. However, recent studies challenged the assumption of such an abstract representation of numerical magnitude (Bulthé et al., 2014; Lyons et al., 2015), and therewith also question conclusions regarding the association of ANS acuity and math anxiety reported so far.

The ANS is assumed to support the comparison and estimation of numerosities (Dehaene, 2001, 2009) and should, therefore, be involved in the solution of a dot comparison task. Importantly, evidence for this assumption was provided by numerous studies with several methodological approaches. Single-cell recordings with monkeys revealed

TABLE 4 | Estimates of fixed effects (log odds) for error rates.

Task	Effect	Estimate (*SE*)	χ^2	*p*	95% CI
Symbolic comparison	Intercept	−3.788 (0.107)	–	–	[−3.998, −3.579]
	Distance	−0.349 (0.244)	242.58	<0.001	[−0.397, −0.302]
	AMAS	−0.012 (0.013)	0.83	0.363	[−0.038, 0.014]
	Size	0.148 (0.010)	234.34	<0.001	[0.128, 0.168]
	Distance × AMAS	0.001 (0.003)	0.03	0.868	[−0.006, 0.007]
	Size × AMAS	<0.001 (0.001)	0.01	0.926	[−0.002, 0.003]
Non-symbolic comparison	Intercept	−0.840 (0.071)	–	–	[−0.980, −0.700]
	Distance	−0.070 (0.008)	70.18	<0.001	[−0.085, −0.054]
	AMAS	0.005 (0.008)	0.47	0.493	[−0.010, 0.020]
	Size	0.009 (0.003)	7.21	0.007	[0.002, 0.015]
	Distance × AMAS	<0.001 (<0.001)	0.05	0.818	[−0.001, 0.001]
	Size × AMAS	<0.001 (<0.001)	1.56	0.212	[>−0.001, <0.001]

P-values were obtained via likelihood ratio tests (df = 1). 95% CI are based on the estimated local curvature of the likelihood surface.

numerosity-selective neurons in the prefrontal and intraparietal cortex responding with a maximum activity to a specific numerosity (i.e., number of dots in a set; Nieder et al., 2002; Nieder, 2012; see also Ditz and Nieder, 2015, for a similar finding in songbirds). However, the neurons fired not exclusively for a specific numerosity, but they were also but less activated by adjacent numerosities. This pattern fitted well to the postulated overlapping Gaussian tuning curves of ANS representations, which increase in their width (i.e., imprecision) as the numerosities increase (Nieder, 2005). Further evidence comes from human brain-imaging studies (e.g., Piazza et al., 2004, 2007; Harvey et al., 2013). For instance, in line with ANS theory Lyons et al. (2015) showed that non-symbolic numerosities are represented by overlapping tuning curves, whereby the neuronal overlap increases with increasing numerosities. Moreover, the pattern of overlapping ANS representations was also reflected by behavioral performance in humans in a delayed match-to-sample task, as the percentage to judge a numerosity matching a sample was highest for the exact match and decreased as the distance between the numerosity of the stimulus and the sample increased (Merten and Nieder, 2009). Hence, several studies evaluating the validity of dot comparison tasks provided conclusive evidence that the dot comparison task assesses ANS acuity (both on a neuronal and a behavioral level). Nevertheless, there are also studies indicating that other cognitive processes are involved in the dot comparison task (e.g., inhibitory control, Fuhs and McNeil, 2013; Gilmore et al., 2013; Clayton and Gilmore, 2015). Moreover, the performance in the dot comparison task was found to be influenced by methodological aspects (e.g., task design, Price et al., 2012; presentation duration of the stimuli, Inglis and Gilmore, 2013; visual parameters, Szűcs et al., 2013). However, our results support the view that the non-symbolic dot comparison task used in our study (also) assessed ANS acuity, as we found both a significant distance and size effect. These effects are considered a result of the imprecise ANS representations and so far there are no alternative explanations for the occurrence of a distance or size effect in non-symbolic comparison tasks. Hence, the distance/ size effects indicate that the ANS was involved in the solution of the task (e.g., Dehaene et al., 1998). Additionally, we were able to fit the Weber fraction to the results of a vast majority of the participants. The Weber fraction is assumed to directly reflect the width of the ANS representations (Pica et al., 2004). Using a non-symbolic dot comparison task, we did not observe a significant association between several indices of ANS acuity and math anxiety. Thus, ANS acuity was not impaired in individuals being more math anxious. Importantly, we not only used the distance and size effect as measures of ANS acuity but also the Weber fraction, which is thought to be the most direct measure of the ANS acuity (Pica et al., 2004). However, comparable to the results for the distance and the size effect, which were already used as measures of ANS acuity in previous studies on the relationship between ANS acuity and math anxiety, we did not find an association between the Weber fraction and math anxiety as well. Moreover, also our Bayesian analysis revealed positive evidence for the null hypothesis.

Taken together, we did not find a reliable association between ANS acuity and math anxiety – independent of the measure used to assess ANS acuity. Therefore, our results are not in line with the conclusion of previous studies (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014) that low ANS acuity is related to and may thus contribute to the development of math anxiety.

Symbolic Number Comparison and Math Anxiety

Our results suggest that ANS acuity does not seem to be related to math anxiety. This raises the question of how to interpret previous and the present results revealing an association of the symbolic distance effect (or size effect) and math anxiety (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014). So far, these results have been explained by less precise magnitude representations in the ANS. However, our results based on the non-symbolic dot comparison task revealed no association between the acuity of the ANS and math anxiety questioning this explanation.

We did not find an overall relationship between math anxiety and performance (i.e., RT and ER) in the symbolic number comparison task. Thus, high math anxious individuals did not *per se* perform worse and/or slower than less math anxious individuals. However, we found a significant association of the distance effect based on RT and math anxiety replicating the findings of previous studies (Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014). Higher math anxious individuals presented with a larger distance effect than those with lower math anxiety. As we did not find a relationship between ANS acuity and math anxiety, this effect cannot be interpreted as being due to less precise magnitude representations in the ANS. Thus, this finding has to be reinterpreted.

There is evidence that the distance effect for symbolic number comparison can be explained by comparison processes (i.e., the connection between the symbolic representation and the response, Van Opstal et al., 2008). In line with this explanation for the distance effect in symbolic number comparison, the association between the distance effect in symbolic number comparison and math anxiety might be due to impaired comparison processes rather than impaired magnitude representations in high math anxious individuals. The connection between the representation and the "which numeral is larger" response might weaker be due to less training of this connection, for example, when math anxious children are not motivated to operate with numbers or avoid working with numbers.

In the present study, we did not find a significant interaction between the size effect for RT and math anxiety. Núñez-Peña and Suárez-Pellicioni (2014) found a tendency for a larger size effect in high math anxious individuals compared to low math anxious individuals. Moreover, compared to our results, the size effect was generally larger in the study of Núñez-Peña and Suárez-Pellicioni (2014). These differences might be due to differences in the design. First, Núñez-Peña and Suárez-Pellicioni (2014) instructed the participants to respond as fast as possible, whereas in the present study the instruction stressed not only speed but also accuracy. Second, in the study by Núñez-Peña and Suárez-Pellicioni (2014) symbolic stimuli were presented for only 300 ms, whereas in the present study stimuli remained visible until a response was given. These two aspects might have induced larger variance in the responses observed by Núñez-Peña and Suárez-Pellicioni (2014), which in turn might have resulted in a larger size effect allowing for a better chance to find a (marginally) significant association of the size effect and math anxiety.

Theoretical Implications

From a theoretical point of view, our results allow for a specification of the model by Ashcraft et al. (2007) who postulated that inadequate basic numerical competencies might constitute a risk factor for the development of math anxiety (Ashcraft and Moore, 2009). According to our findings this risk factor might include deficits in symbolic number comparison. More precisely, our results indicate that comparison processes seem to be impaired in high math anxious individuals, because math anxiety was associated with the symbolic distance effect (Van Opstal et al., 2008). Further evidence for our conclusion that deficits in symbolic number comparison might indeed constitute a risk factor for the development of math anxiety [as suggested by Ashcraft et al. (2007)] comes from studies indicating a general relationship between the distance effect in symbolic number comparison and math performance (e.g., Holloway and Ansari, 2009). One mechanism for the development of math anxiety according to the model of Ashcraft et al. (2007) is that inadequate math skills lead to math performance deficits, which in turn support the development of math anxiety. Thus, deficits in basic numerical abilities such as the comparison of symbolic numbers should be associated with lower math performance. In line with this suggestion De Smedt et al. (2009) found that the symbolic distance effect for RTs predicted later math performance, whereby a larger distance effect was associated with lower later math performance. In turn, according to the model of Ashcraft et al. (2007) lower math performance contributes to the development of math anxiety. And thus, a more pronounced distance effect should be associated with higher math anxiety, which is exactly what we found (see also Maloney et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2014).

However, it remains an open question what causes the larger symbolic distance effect in more math anxious individuals. When interpreting this effect as impaired comparison processes this might be explained by less trained connections between the symbolic representation of the number and the response. This finding might be due to an insufficient motivation of the children to work with the numbers. Insufficient motivation is another risk factor according to the model of Ashcraft et al. (2007). Thus, both risk factors inadequate math skills and insufficient motivation might be strongly inter-related. Additionally, the less trained connections might also reflect the tendency to avoid working with numbers. Due to the low difficulty of the task the lower practice of working with numbers might solely be reflected in the more difficult trials (i.e., trials with small distance between the two numbers).

Moreover, we specifically investigated whether a deficient ANS (assessed using a non-symbolic dot comparison task) may be a risk factor according to the model of Ashcraft et al. (2007). However, we found that ANS acuity was not associated with math anxiety. Thus, our results did not provide evidence for the hypothesis that a deficient ANS might be a risk factor for the development of math anxiety. Similarly, our results do not support the hybrid model of Maloney et al. (2011) who postulate that a less precise ANS plays a role in the development of math anxiety, since we did not find a relationship between ANS acuity and math anxiety.

CONCLUSION

Taken together, our findings question the previous conclusion that a less precise ANS is associated with higher math anxiety. Our results revealed that ANS acuity – when being measured by the standard ANS task (i.e., a non-symbolic dot comparison task) – was not associated with math anxiety at all. However, we replicated the association of the distance effect for symbolic number comparison and math anxiety. Thus, impaired processes in symbolic but not non-symbolic magnitude comparison seem to underlie math anxiety. Generally, this finding fits nicely in the model of Ashcraft et al. (2007), who proposed that inadequate basic numerical competencies constitute a risk factor for the development of math anxiety. According to our results this risk factor might also include impaired symbolic number comparison processes.

FUNDING

Julia Dietrich was supported by the German Research Foundation (DFG) providing funding to Korbinian Moeller and Elise Klein (MO 2525/2-1). Stefan Huber was supported by the Leibniz-Competition Fund providing funding to Elise Klein (SAW-2014-IWM-4). Elise Klein was supported within the Margarete von-Wrangell Fellowship by the European Social Fund (ESF) and by the Ministery Science, Research and the Arts Baden-Wuerttemberg.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01621

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 16 October 2015
doi: 10.3389/fpsyg.2015.01539

Attentional bias in math anxiety

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Cognitive theory from the field of general anxiety suggests that the tendency to display attentional bias toward negative information results in anxiety. Accordingly, the current study aims to investigate whether attentional bias is involved in math anxiety (MA) as well (i.e., a persistent negative reaction to math). Twenty seven participants (14 with high levels of MA and 13 with low levels of MA) were presented with a novel computerized numerical version of the well established dot probe task. One of six types of prime stimuli, either math related or typically neutral, was presented on one side of a computer screen. The prime was preceded by a probe (either one or two asterisks) that appeared in either the prime or the opposite location. Participants had to discriminate probe identity (one or two asterisks). Math anxious individuals reacted faster when the probe was at the location of the numerical related stimuli. This suggests the existence of attentional bias in MA. That is, for math anxious individuals, the cognitive system selectively favored the processing of emotionally negative information (i.e., math related words). These findings suggest that attentional bias is linked to unduly intense MA symptoms.

Keywords: math anxiety, dot probe, attentional bias

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Edited by:
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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *29 July 2015*
Accepted: *23 September 2015*
Published: *16 October 2015*

Citation:
Rubinsten O, Eidlin H, Wohl H and Akibli O (2015) Attentional bias in math anxiety. Front. Psychol. 6:1539. doi: 10.3389/fpsyg.2015.01539

Introduction

Mathematical skills are essential for productive functioning in our progressively more complex, technological society. In addition, numerical development has been a focus of the continuing theoretical debate concerning the origins of cognition and how it develops throughout one's lifetime. Numerical difficulties result in reduced educational and employment achievements, and in increased physical and mental health costs (Woloshin et al., 2001; Parsons and Bynner, 2005; Duncan et al., 2007; Reyna et al., 2009). Some argue that in western society, poor numeracy is a greater handicap than poor literacy (e.g., Rivera-Batiz, 1992; Estrada et al., 2004). Hence, mathematical skills may have an impact on social mobility and poverty levels.

However, some people find it difficult to learn arithmetic or mathematics since they suffer from math anxiety (henceforth math anxiety, or MA), which is a persistent negative reaction to math, ranging from mild discomfort to extreme avoidance (Hembree, 1990; Ma and Xu, 2004a,b; Ashcraft and Ridley, 2005). Given the implications of MA, a systematic identification of the vulnerability factors that contribute to the development and maintenance of MA is crucial. But what are these possible vulnerability factors? According to information processing theories, fear and anxiety may be caused by different cognitive processes, such as attention. Compared to non-anxious individuals, anxious individuals are more likely to show an inclination to attend to threatening stimuli over non-threatening stimuli in their environment (attentional bias) (for review see Van Bockstaele et al., 2014). Attentional bias to threatening stimuli was found for general, but not MA. The current study aims to fill this gap.

Math anxiety consists of feelings of tension (Richardson and Suinn, 1972) and low self confidence in one's ability to learn mathematics (Jain, 2009). In addition, MA can affect general cognitive abilities such as decline in working memory (Ashcraft and Kirk, 2001). Cognitive causes may also involve core numerical characteristics such as counting abilities (Maloney et al., 2010), the precision of the mental number line (Maloney et al., 2011), and poor numeracy (i.e., the ability to estimate large quantities of items – Rubinsten and Tannock, 2010). MA was also found to have a possible genetic (Wang et al., 2014) and a specific neural basis (Young et al., 2012), even when only anticipating math problems (Lyons and Beilock, 2011); this was found in the bilateral inferior frontal junction, a brain region known to be involved in cognitive control and reappraisal of negative emotional responses. The more highly math anxious individuals activated this frontoparietal network before they even engaged in mathematics; the better they performed on a math task.

In terms of epidemiology, recent findings show that even children as young as the first grade suffer from MA (Ramirez et al., 2013). In addition, although there are exceptions, most studies of MA report higher levels of MA for females than for males (e.g., Betz, 1978; Hembree, 1990; Ashcraft and Faust, 1994; Hopko, 2003; Ma and Cartwright, 2003; Haynes et al., 2004; Baloglu and Kocak, 2006; McGraw et al., 2006; Jain, 2009; Else-Quest et al., 2010). However, other studies failed to find such a gender difference (e.g., Cooper and Robinson, 1991). These gender differences appear despite the fact that no difference is typically found between genders in math knowledge and skills (for a meta-analysis see Else-Quest et al., 2010).

Even mild levels of MA have been associated with academic decisions (Brown et al., 2010). This may suggest that MA may be a strong antecedent for the low visibility of women in the science and engineering workforce. For example, despite gender similarities in math achievements (Hedges and Nowell, 1995; Hyde et al., 2008; Else-Quest et al., 2010) or even better math grades for females compared to males (Kenney-Benson et al., 2006), in the US women constitute only 28% of the science and engineering workforce (correct for the year of 2010 – National Science Foundation, 2013). Women are also severely underrepresented in math-intensive fields (Ceci and Williams, 2011). Hence, as our society becomes progressively more dependent on math, failure to acquire numerical skills may increasingly act as a filter, preventing occupational success for men but mainly for women (e.g., Halpern et al., 2007). This makes it a very good reason to study MA.

The current study aims to investigate the cognitive source of MA. It is still quite rare to see cognitive neuroscience research take into account issues of MA, and only scant attention has been devoted to the antecedents of MA. By suggesting the role played by anxiety in numerical situations, scientists and clinicians will be better able to provide cognitive models of both MA vulnerability and math dysfunction.

As mentioned above, the antecedents and epidemiology of MA are still being studied and results are inconclusive. One variable that might be related to different findings regarding MA is the common use of explicit tools such as the MA rating scale (e.g., Richardson and Suinn, 1972), the MA questionnaire (Wigfield and Meece, 1988) (for a German version see Krinzinger et al., 2007), the abbreviated math anxiety scale (AMAS: Hopko et al., 2003), or the revised Math Anxiety Rating Scale (MARS-R: Alexander and Martray, 1989; Hopko, 2003) to diagnose MA. Such explicit tools typically assess accessible self representations.

However, women, for example, have been found to score higher than men on self-report measures of trait anxiety (e.g., Feingold, 1994; Costa et al., 2001; Egloff and Schmukle, 2004), possibly resulting from gender differences in anxiety that are not due to anxiety *per se*. That is, gender differences in explicit self-report questionnaires could be the result of greater willingness of women to disclose personal attitudes (Ashcraft, 2002). Indeed, Flessati and Jamieson (1991) argued that gender differences in MA could be explained by the fact that females are more self-critical of their performance.

Implicit measures, on the other hand, typically assess inaccessible cognitive structures or representations that are processed automatically. It has been shown that affective traits can be activated automatically and influence emotional, cognitive, and behavioral processes (e.g., Giner-Sorolla et al., 1999) even in the case of MA (Rubinsten et al., 2012). That is, affective processing begins immediately and even involuntarily upon seeing a salient affective word or picture (for review see Rubinsten, 2015).

Thus, one of our primary objectives is to investigate cognitive characteristics of MA, and specifically attentional bias, by using a novel attention bias task as an indirect measure.

Math anxiety has been found to be positively, albeit moderately, correlated with general, state, and trait anxiety (Ashcraft and Moore, 2009). General anxiety is traditionally classified into two distinct components, "trait" and "state." While trait anxiety refers to relatively stable individual differences in anxiety proneness, state anxiety is a transitory emotional condition (Spielberger and Spielberger, 1966). Mathematics anxiety is conceptualized as a situation (i.e., trait) specific anxiety that manifests itself in mathematics-related environments (e.g., Baloglu, 1999). These similarities between general and MA, may suggest that the cognitive traits that are associated with general anxiety, such as the tendency to ruminate over negative thoughts and stressful situations (Donaldson et al., 2007) or the tendency to display attentional bias toward negative information (Bar-Haim et al., 2007), are involved not only in general anxiety but also in MA. Interestingly, and to the best of our knowledge, contemporary scientific approaches have not availed themselves of this insight, which suggests a link between the cognitive symptoms of general and MA. Accordingly, here we wish to focus on attentional bias in MA via an implicit and novel cognitive tool.

Rumination is defined as repetitive thinking about negative personal concerns and/or about the implications and causes of a negative mood (Nolen-Hoeksema et al., 2008). Indeed, the tendency to ruminate has been associated with self-reported symptoms of generalized anxiety (Fresco et al., 2002; Harrington and Blankenship, 2002), post-traumatic stress (Nolen-Hoeksema and Morrow, 1991; Clohessy and Ehlers, 1999; Mayou et al., 2002), and social anxiety (Mellings and Alden, 2000).

Rumination affects the ability to remain attentive to the task at hand due to obsessive thoughts over negative feelings (Donaldson et al., 2007). Reese et al. (2010) have suggested that attentional bias to negative information is linked to the repetitive negative thinking characteristic of anxious rumination and worry. Indeed, rumination and attentional bias have been linked to stress and to each other (e.g., Bradley et al., 1997; Beevers and Carver, 2003; Mogg and Bradley, 2005). Morrison and O'Connor (2008) even suggested a causal relationship in which rumination affects attentional bias. Hence, clinically anxious patients have been shown to display attentional bias toward negative information (Bar-Haim et al., 2007). It has been suggested that biased patterns of information processing (such as rumination and attentional bias) operate within the cognitive system at a very early stage and hence, are unreachable to awareness and play a central causal role in susceptibility to experiencing overly intense general anxiety symptoms (Mathews and MacLeod, 2005). Another approach concerning the link between anxiety and attention is described by the attentional control theory suggested by Eysenck et al. (2007). According to the attentional control theory, the anxiety state is capable of increasing the allocation of attention to threat related stimuli. That is, anxiety typically reduces attentional focus on a current task unless it involves threatening stimuli; or in other words anxiety impairs attentional control. Therefore, we aim to examine attentional bias in MA and to suggest that it is attentional bias that leads to unduly intense MA symptoms and to damage to information processing (i.e., solving math problems). This suggestion of ours, is based on cognitive theory from the field of general anxiety (Beck et al., 1979), which posits that certain cognitive vulnerabilities (such as attentional bias), when 'activated' by stressful or negative life events, result in psychological distress.

Attentional bias has been assessed in various ways. One technique is the visual probe task, in which stimuli that differ in their emotional tone are briefly exposed on a computer screen before a visual probe appears in the locus where one or another emotional stimuli were exposed (Koster et al., 2006; Colin et al., 2007). Participants must quickly discriminate probe identity. Typically, responses are found to be faster when probes appear in the locus of negative stimuli. Hence, attentional bias in the dot probe task could arise from fast responding in congruent trials (attentional engagement to threat), slow responding in incongruent trials (slow attentional disengagement away from threat), or a combination of both (e.g., Koster et al., 2004). Such a pattern of results provides an index of selective attention to negative or threatening information. This dot probe task has showed attentional bias to negative stimuli in both clinical and non-clinical expressions of anxiety (Cisler and Koster, 2010).

The purposes of the current study are to strengthen MA assessment (i.e., by using an implicit instead of an explicit tool) and to focus on attention bias in MA. For that, we developed a novel computerized numerical version of the well established dot probe task (MacLeod et al., 1986), which has been proven to be a highly reliable tool in the assessment and even treatment of general anxiety (e.g., Baert et al., 2010). We hypothesized that math anxious individuals would react faster when the probe is at the location of the threat/numerical related prime (e.g., based on Bar-Haim, 2010). That is, as in the typical dot probe task, faster reaction times (RTs) when probes appear in the locus of numerical primes, will point to selective attention to negative information (i.e., attentional bias in MA).

Materials and Methods

Participants

Twenty-eight adults participated in the study (nine males, mean age = 26.44 years, $SD = 4.61$). One female participant was excluded due to missing data. All participants were recruited through advertisements distributed on a university campus. All participants gave their written consent to participate in the experiment and were paid about 10USD for their participation. The recruitment, payment, task, and overall procedure were authorized by the research ethics committee of the university.

Classification and Assessments Criteria

Participants were sorted into groups of MA as follows: high math anxiety (HMA) or low math anxiety (LMA), based on their score on the MARS-R questionnaire (Plake and Parker, 1982). The cut-off threshold for inclusion was a score below (for the LMA group) or above (for the HMA group) 72 points, which was the group median score. An independent *t*-test yielded significant differences between HMAs (14 participants of whom 4 were males, $M = 83.4$, $SD = 10.83$) and LMAs (13 participants of whom five were males, $M = 57.9$, $SD = 11.8$) on the MARS-R scores [$T_{(25)} = 5.8$, $p < 0.001$]. It is interesting to note that no gender difference was found in the MARS-R scores [$T_{(24)} = -1.1$, n.s.].

The Experimental Tasks and Stimuli

The novel numerical dot probe task

Stimuli

A novel dot probe task was created for the experiment, based on the method of the well established dot probe task initially developed by MacLeod et al. (1986). A prime stimuli, either math related (a math equation such as 26 + 65 or a math word such as "quantity") or typically neutral (a word with neutral valence such as "table"), are presented on one side of a computer screen, and are then preceded by a probe (either one or two asterisks "*") that appears in either the prime location (congruent) or the opposite location (incongruent). Participants must quickly discriminate probe identity (one or two asterisks) and then preform a task regarding the prime stimuli.

One of six types of primes appeared on either the left or right side of the computer screen. There were four different equation levels. Accordingly, the prime could be either a single digit arithmetic equation (e.g., 8–4), a double digit (e.g., 52 + 16), a triple digit (e.g., 536/268), or a power equation (e.g., $9^2 \times 3^5$), math word (e.g., number), or neutral word (e.g., pencil).

Each equation level (i.e., single, double, triple digit, or power) contained four pairs of numbers (e.g., 8 and 4). Each pair of numbers produced four trials: each type of these trials involved one of the four basic operations: addition, subtraction, multiplication, or division (e.g., the pair 8 and 4 produced the equations 8 + 4, 8 − 4, 8*4, and 8/4). There were three major rules for pair matching: (1) Each pair of numbers was chosen based on numerical length (either single, double, or triple digits). (2) One number in each pair was a multiplication of the other. (3) Digit frequency (1–9) was controlled across all numerical combinations (for a detailed list of the numbers, see Appendix 1).

The word stimuli consisted of 16 math related words and 16 neutral words. All words were chosen based on their frequency and emotional load. Frequency levels and emotional load were tested by a short questionnaire distributed online (by Google form document) to 58 university students. For each item participants were asked how familiars the word on a 9 point Likert scale (1- not familiar, 9- very familiar) and how frightening is the word on a 9 point Likert scale (1- not frightening at all, 9- very frightening). The words were also matched by their length, i.e., number of letters (for detailed information see Appendix 1).

The prime appeared on a black background and was positioned on one side of the computer screen at a 3.81° (short stimuli) – 16.84° (long stimuli) visual angle (VA; VA was calculated using the following formula: $\theta = 2\tan^{-1}(\frac{s}{2d})$ where d is the distance between the participant's eye and the screen and s is the size of the object on the screen).

The prime presentation was followed by a probe identification task. The probe was either one (i.e., *) or two asterisks (i.e., **).The probe could appear on the same side previously occupied by the prime (i.e., congruent trial) or on the opposite side (i.e., incongruent trial). In order to avoid visual bias, the probe's exact location was chosen randomly, so it could appear at seven different locations on each side of the screen, matching all possible locations previously occupied by the prime (either by the numbers of the math equation or the letters of the words). Participants were asked to determine if there were one or two asterisks (first task – see **Figure 1**). Following the probe identification task, and after the participant responded to the probe, the probe disappeared and either a number (after math equation prime) or a word (after word prime) appeared in the center of the computer screen. Participants were asked (second task) to determine whether the number was the correct answer to the previously presented equation (i.e., prime) or not. In cases of word prime trials, participants had to determine, in this second task, whether the word that appeared in the center of the screen rhymed with the previous word or not. This second task was presented in order to make sure that participants indeed processed the prime and to create meaningful math stimuli.

Procedure

Each trial in our numerical dot probe task began with a white colored square shaped fixation point, presented for 750 ms and followed by a blank screen presented for 100 ms. Then, a prime appeared on either the left or the right side of the screen and remained for 1000 ms. Next, there was an inter stimulus interval (ISI) of 100–150 ms (the exact ISI changed in between stimuli to avoid participant prediction of the stimuli's appearance for similar rationale and ISI see e.g., Posner and Boies, 1971). Afterward, a small probe (one or two asterisks) appeared either on the side previously occupied by the prime (congruent trial) or on the opposite side of the screen (incongruent trial). Participants were instructed to determine whether one or two asterisks appeared on the computer screen by pressing one

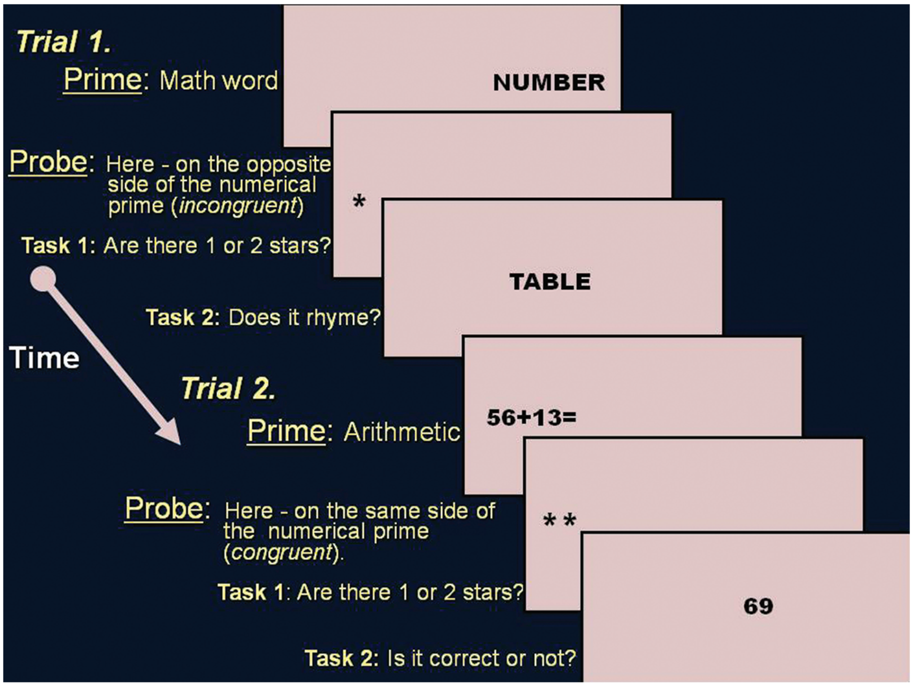

FIGURE 1 | Examples of stimuli in the numerical dot probe task.

of two optional keys on the keyboard (the numbers 1, 2). Half of the participants were asked to use their right hand to respond and half used their left hand. The probes remained on the computer screen until the participant responded or for 3000 ms. Then a number or a word appeared in the center of the screen (task 2 – see **Figure 1**) and participants had to determine whether the number/word was the correct answer to the equation/rhymed with the previous word or not and to press a matching key on the keyboard (1 for correct answer and 2 for wrong answer). After responding or after 4000 ms a black screen appeared and remained for 1500 ms (for illustration of the trials see **Figure 1**). Following this period of time, the next trial began.

The task contained six blocks, each comprised of one sample of each stimuli type (four equation levels, math related and neutral words). In order to avoid ongoing stress levels, each block was followed by a 1 min break, during which an aquarium film appeared on the computer screen. Overall, the task consisted of 96 trials and lasted about 45 min.

The Revised Mathematics Anxiety Rating Scale

Participants answered a Hebrew translated computerized version of the *MARS-R* (Plake and Parker, 1982), which is a shortened version of the MARS questionnaire (Richardson and Suinn, 1972) containing 24 items. We created the computerized version using an online Google form document, completed by participants after performing the experimental task. The computerized version allowed us, among other things, to make sure that participants did not miss any questions.

The questionnaire was designed to reflect the degree of anxiety experienced in a variety of math related tasks and situations, based on 5-point Likert scale (1- not nervous at all to 5- very nervous). In order to obtain the total score, we simply summed up the scores for all questions. Since the literature does not set a clear threshold that represents HMA levels and based on the methods of previous studies, a median score of 72 points and higher (obtained by giving a rating of 3 or higher for each question) was chosen as representing HMA levels.

Results

Probe Identification Task (Task 1) – Accuracy Rates

Accuracy rates for the probe identification task were very high following all types of primes (single digits: $M = 0.97$, $SD = 0.05$; double digits: $M = 0.96$, $SD = 0.04$; triple digits: $M = 0.96$, $SD = 0.07$; powers: $M = 0.98$, $SD = 0.04$; math word: $M = 0.96$, $SD = 0.05$; neutral word: $M = 0.94$, $SD = 0.06$).

Solution Task (Task 2) – Accuracy Rates

Mean accuracy rates for deciding whether the number presented is the correct solution of the prime (i.e., task 2; see **Figure 1**) was very low in both the power (40%) and triple digit (30%) equations. Mean accuracy rates of all the other equations and words were higher than 80%. Since our aim was to have all participants mentally process the prime and to make sure that the primes contain meaningful math stimuli, we did not analyze the triple and power equation. This was done under the assumption that at some point participants ignored the triple digit and the power equation, as they were too difficult or complicated to solve mentally.

We then conducted two-way repeated measures ANOVA on the prime accuracy rates (task 2). This analysis included the Anxiety group (HMA or LMA) as the between-subject factor and Prime type (i.e., single digits, double digits, math word, neutral word) as the within-subject factor.

There was neither significant difference between the groups ($F < 7$) in accuracy rates nor interaction between Group and Prime type.

Solution Task (Task 2) – Reaction Time

There was no significant difference between the groups ($F < 10$) in RTs nor interaction between Group and Prime type.

Dot Probe Analysis – Reaction Time

A four-way repeated measures ANOVA was conducted on the probe's mean RTs. This analysis included the Anxiety group (HMA or LMA) as the between-subject factor and Prime type (i.e., single digits, double digits, math word, neutral word), Congruency (prime and probe congruent, vs. prime and probe incongruent), and Operation (i.e., addition, subtraction, multiplication, and division) as within-subject factors.

Only trials, in which the probe was correctly identified, were analyzed.

Because Mauchly's Test of Sphericity indicated that circularity could not be assumed, all of the following *F*-statistics are adjusted by the Greenhouse-Geisser correction.

The results revealed a main effect of Prime type [$F_{(3,69)} = 31.8$, $p < 0.001$, $\eta^2 = 0.55$], such that RTs for probes presented after single digit equations were faster ($M = 841.9$, $SD = 49$) than after double digit equations ($M = 958.4$, $SD = 51.8$) and both were slower than probes presented after neutral words, which were processed faster ($M = 689.4$, $SD = 35.5$) than math words ($M = 748$, $SD = 46.2$). No other main effects were evident (e.g., main effect of Group $F < 8$ not significant).

The triple interaction between Group × Type × Congruency was significant [$F_{(3,69)} = 3.77$, $p = 0.05$, $\eta^2 = 0.16$] (see **Figure 2**). We further conducted simple interactions of Group × Congruency separately for math related probes (i.e., single and double digits and math words).

Math Related Probes

The simple interaction between Group and Congruency was significant [$F_{(1,25)} = 4.1$, $p = 0.05$, $\eta^2 = 0.14$]. The simple main effect of congruency was significant in the *HMA group* [$F_{(1,13)} = 31.8, p > 0.001$], indicating that congruent probes were processed significantly faster ($M = 723$ ms) than incongruent probes ($M = 925$ ms). This simple main effect of congruency was not significant in the *LMA group*.

Neutral Words

The simple interaction between Group and Congruency was not significant.

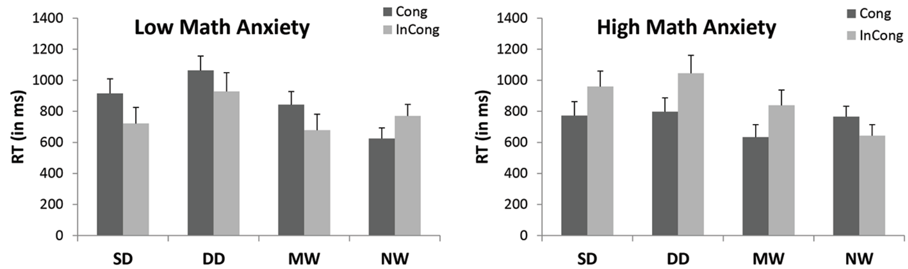

FIGURE 2 | Mean reaction times (RTs) of type of probe and congruency as a function of group (significant interaction between Group, Probe, and Congruency). SD, single digit equations; DD, double digit equations; MW, math words; NW, neutral words. Cong, congruent (i.e., probe and prime are presented at the same location); InCong, incongruent (i.e., probe and prime are presented at opposite locations). Error bars denote the standard error of the mean.

It is interesting to note that when analyzing the simple interaction of Group × Congruency in math words only, the interaction was significant [$F_{(1,25)} = 4.2$, $p = 0.017$, $\eta^2 = 0.14$]. The simple main effect of congruency was marginally significant in the HMA group [$F_{(1,13)} = 2.09$, $p = 0.17$], indicating that congruent probes were processed faster ($M = 627$ ms) than incongruent probes ($M = 814$ ms). This simple main effect of congruency was not significant in the LMA group.

In an additional different analysis we looked at MA scores as a continuum. Specifically, in the current analysis we correlated MA scores (MARS) with the mean congruency effect (incongruent – congruent) for the math related trials. This correlation was found to be significant and positive [$r = 0.4$, $p < 0.05$], indicating that the higher the MA the larger the effect.

Discussion

The appearance of biases in the cognitive processes of individuals with general anxiety has been highlighted as a distinction of the etiology, maintenance, and treatment of anxiety disorders (Beck and Clark, 1997). Specifically, there is accumulating evidence that anxiety is associated with a bias in early preattentive processes that are likely to be involved in initial orienting of attention toward threat stimuli. How do we go about linking this characteristic to the cognitive profile that defines MA? We identified here two possible accounts for clarifying the cognitive status of MA: (1) math is associated with negative valence, and (2) attentional bias is related to numerical information. Broadly speaking, these claims respectively indicate that for math anxious individuals, math related stimuli such as math words or math equations are cognitively or affectively linked with threatening and negative valence (Rubinsten and Tannock, 2010; Rubinsten et al., 2012). Accordingly, for math anxious individuals, the cognitive system selectively favors the processing of emotionally negative information (e.g., math related words). Though not directly measuring selective attention to numerical information, the previous findings of Rubinsten and Tannock (2010) and Rubinsten et al. (2012) pointed to selective attention to negative information and support current findings. Indeed, current findings show, as in the typical dot probe task, faster RTs in HMAs, when probes appear in the locus of the numerical prime (i.e., either single and double digit equations or math words). Such a congruency pattern (i.e., faster RTs for congruent than for incongruent trials) was not found in the case of neutral word primes; or at least, high math anxious individuals processed neutral words similar to low MA individuals. It is important to note that there was no significant main effect of RT between the two groups; HMAs was not generally slower. Moreover, there was no significant main effect of accuracy levels between the groups either for detecting the probe or for solving the math equations. Hence, HMAs did not show lower performance and did not need additional time in order to solve the tasks. That is, the longer time it took the HMA group to locate the congruent probe (compared to the incongruent) is due to the threatening affect associated with the math equation and not since these equations were too complicated to solve.

Several authors have tried to further differentiate between different components of attention (engagement, disengagement, and shifting – see Posner and Petersen, 1990) in the dot probe task (Koster et al., 2004, 2006; Salemink et al., 2007). However, and since the measurement of the separate components has been previously challenged, there is general agreement that the dot probe task is a useful measure of attentional bias as a single entity that includes all of these components. Hence, and because the focus of our study is attentional bias as a single entity in MA, we cannot reach a conclusion about the different components of attention. However, the long presentation time of the prime in the current study (1000 ms) may suggest that math anxious individuals show a general bias in cognitive processing, and hence, once their attention has settled on a threatening numerical stimulus, they have successive difficulty in disengaging it.

Specifically, Bradley et al. (1998) examined biases in initial shifting versus maintenance of attention, by manipulating the exposure duration of the threatening prime stimulus. Their results indicated that the attentional bias for threat was not significantly different between the two different exposure durations (500 and 1250 ms). Given that the duration of 1250 ms in Bradley's study and 1000 ms in the current study potentially allow multiple shifts of attention, our results (based on the findings of Bradley et al., 1998) may suggest that attentional bias in anxiety operates in both initial orienting and in the maintenance of attention – math anxious individuals do not disengage attention from the negative stimulus. This view is compatible with Beck's (1979) model, which suggests that anxiety related biases favoring threat stimuli operate on both attentional levels (i.e., initial orienting and maintenance of attention).

Attentional bias allows the cognitive system to prioritize specific stimuli for processing. Accordingly, responding to threats may in fact facilitate survival and learning. For example, mammals tend to learn mainly about those aspects of the environment to which they attend (for review see Shechner et al., 2012). Following this line of logic, it would be expected that math anxious individuals, who present attentional bias toward numerical contents, will show better learning curves and better math performance. This is of course not the case. We show no significant differences in accuracy rates between high and low math anxious individuals, and previous studies have shown low math performance in MA (e.g., Maloney et al., 2010; Rubinsten and Tannock, 2010). Accordingly, it may be suggested, although not directly studied here, that attentional bias is related to rumination, which directly impacts performance and significantly affects individuals' ability to remain attentive to the task at hand (Donaldson et al., 2007). Indeed, Reese et al. (2010) suggested that attentional bias to negative information may be the factor that contributes to the pattern of distressing and repetitive negative thinking that characterizes anxious rumination and worry. Accordingly attentional bias and rumination in the case of MA, suggest constant obsessive thoughts over negative feelings related to math and the stress that mathematical problems cause, consequently turning attention away from the ways in which one can actually solve these problems (Ashcraft and Moore, 2009; Beilock and Ramirez, 2011).

It is important to note that, due to methodological limitations, the vital question of causality (between attentional bias and MA) cannot be answered here. This causality question is nevertheless crucial, not only from a scientific perspective but also from a clinical perspective. If cognitive and, specifically, attentional biases are causally involved in the development of MA, then therapeutic interventions should aim to reduce these cognitive biases to prevent or reduce the individual's level of anxiety.

There are some additional limitations in the current study, such as small sample size or no information on general anxiety levels. However, the significant triple interaction between group, congruency, and type of equation may suggest that sample size was sufficient to answer the current research question. Importantly, though, it should be noted that participants in the current study were divided into high vs. low MA groups using a median split. Some argue that a median split to dichotomize the scores may not be the most valid method of assessing high or low levels of participants (Waller and Meehl, 1998). Hence, it might be claimed that our group selection criteria may not be the best to answer current research questions. This indeed might be the case and could be considered a limitation and yet it should be mentioned that several other studies in the field of MA used a similar criterion for different tests (e.g., 2 working memory groups, Beilock and DeCaro, 2007; Ramirez et al., 2015).

Conclusion

The current findings show that math anxious individuals shift their attention toward numerical stimuli, which for them are associated with negative and threatening valence. That is, this study strongly implicates biased processing of threats in the maintenance of MA. Attention is highly relevant for several other cognitive processes, such as memory and other forms of learning. Hence, the study of attention biases appears particularly pertinent to MA research, as attention affects learning and, specifically, math learning.

Acknowledgments

Work by OR was conducted under the auspices of the Center for the Study of the Neurocognitive Basis of Numerical Cognition, supported by the Israel Science Foundation (grant number 1664/12) as part of their Centers of Excellence.

Supplementary Material

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01539

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 19 October 2015
doi: 10.3389/fpsyg.2015.01577

Attentional bias in high math-anxious individuals: evidence from an emotional Stroop task

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Attentional bias toward threatening or emotional information is considered a cognitive marker of anxiety, and it has been described in various clinical and subclinical populations. This study used an emotional Stroop task to investigate whether math anxiety is characterized by an attentional bias toward math-related words. Two previous studies failed to observe such an effect in math-anxious individuals, although the authors acknowledged certain methodological limitations that the present study seeks to avoid. Twenty high math-anxious (HMA) and 20 low math-anxious (LMA) individuals were presented with an emotional Stroop task including math-related and neutral words. Participants in the two groups did not differ in trait anxiety or depression. We found that the HMA group showed slower response times to math-related words than to neutral words, as well as a greater attentional bias (math-related – neutral difference score) than the LMA one, which constitutes the first demonstration of an attentional bias toward math-related words in HMA individuals.

Keywords: attentional bias, emotional Stroop task, math anxiety

OPEN ACCESS

Edited by:
Irene Cristina Mammarella, University of Padova, Italy

Reviewed by:
Kinga Morsanyi, Queen's University Belfast, UK
Maria Chiara Passolunghi, University of Trieste, Italy

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *21 July 2015*
Accepted: *29 September 2015*
Published: *19 October 2015*

Citation:
Suárez-Pellicioni M, Núñez-Peña MI and Colomé À (2015) Attentional bias in high math-anxious individuals: evidence from an emotional Stroop task. Front. Psychol. 6:1577. doi: 10.3389/fpsyg.2015.01577

INTRODUCTION

Why do students with similar math ability choose alternative academic pathways at university? LeFevre et al. (1992) constructed a regression model to predict students' choices of university majors varying in mathematical content and found that whereas age, fluency in math and experience with math contributed significantly to the choice, a "math affect" factor, comprising math anxiety and measures of avoidance toward math, more than doubled the variance accounted for by the model. Math anxiety has been defined as a feeling of tension, apprehension or even dread that interferes with the ordinary manipulation of numbers (Ashcraft and Faust, 1994). The negative effect of anxiety is reflected in poorer performance among high math-anxious (HMA) individuals (hereinafter, HMA), which, in turn, generates feelings of failure and, consequently, avoidance of this subject in the academic curriculum. As such, math anxiety leads people who are perfectly capable of doing math to distance themselves from mathematical contents and to feel afraid of the subject (for a recent review on the topic see Suárez-Pellicioni et al., 2015).

Although not recognized as a clinical condition, math anxiety is nonetheless a type of anxiety. Indeed, research has shown that findings related to other types of anxiety can be extended to the field of math anxiety. For example, as previously shown for generalized anxiety disorder or obsessive compulsive disorder (e.g., Gehring et al., 2000), a greater *error-related negativity* (i.e., an ERP component appearing approximately 150 ms after error commission) has been found in HMA individuals for errors committed in a numerical Stroop task but not in a control one (Suárez-Pellicioni et al., 2013b). Similarly, the reactive recruitment of attentional control observed for high trait anxious individuals (Osinsky et al., 2012) was also found for HMA ones, who exerted attentional control only after incongruent trials on a numerical Stroop task (Suárez-Pellicioni et al., 2014). Finally, several cognitive theories (Williams et al., 1988) have postulated that attentional bias toward threatening information can be considered a cognitive marker of numerous types of anxiety (Beck et al., 1985). In this respect, a wealth of research has confirmed that only anxious individuals display an attentional bias toward threatening information (Williams et al., 1996; Mogg and Bradley, 1998; Bar-Haim et al., 2007).

Similarly, the general theories trying to explain the negative effects of anxiety on performance have also been useful for explaining the negative effects of math anxiety on math performance. For example, the pioneering researchers on math anxiety (Ashcraft and Faust, 1994; Faust et al., 1996) interpreted their findings in the context of the *Processing efficiency theory* (PET; Eysenck and Calvo, 1992), one of the most important theories trying to explain the relationship between anxiety and performance in cognitive tasks. According to this theory, the anxiety reaction generates intrusive worrying thoughts that consume the limited attentional resources of the central executive of working memory (WM), which are then less available for task processing. Following this line, Ashcraft and Faust (1994) claimed that math anxiety affected performance only when complex –but not simple-arithmetic was involved and this effect would be due to HMA individuals devoting their WM resources to processing the worrying intrusive thoughts generated by the math anxiety reaction, instead of using them in solving the cognitive task.

In this line, this theory also claimed that anxiety affects *processing efficiency* (i.e., the relationship between the quality of performance and the amount of resources or effort needed to attain a given performance level) to a greater extent than *performance effectiveness* (i.e., quality of performance). In line with this theory, we found that although HMA and LMA participants did not differ in their level of performance in a simple addition verification task (i.e., no differences in performance effectiveness), the groups differed in processing efficiency, the HMA group investing more attentional resources (i.e., P600/P3b amplitude) than their LMA peers when a number far away from the correct solution (i.e., large-split) was presented as the proposed solution for the addition (Suárez-Pellicioni et al., 2013a).

However, the PET (Eysenck and Calvo, 1992) was questioned because of lacking precision and explanatory power, so a more recent theory, the *Attentional control theory* (ACT; Eysenck et al., 2007) emerged to improve those aspects. According to this theory, the specific function of WM affected by anxiety is attentional control, with anxiety causing an imbalance between the *stimulus-driven attentional system* (bottom-up) and the *goal-directed attentional system* (top-down). Given that HMA individuals would be more influenced by the former system, they would be more vulnerable to bottom-up attentional intrusions, that is, more vulnerable to distraction. In this respect, HMA individuals' vulnerability to distraction was demonstrated by several studies, such as Suárez-Pellicioni et al. (2013a), who interpreted that this vulnerability would be at the base of HMA individuals' difficulties in processing the above mentioned large-split solutions. More concretely, it has been considered that this imbalance between attentional systems would have its most detrimental effects on the inhibition function (Eysenck et al., 2007).

In this respect, several researchers have demonstrated that HMA individuals show greater difficulties to inhibit the influence of irrelevant information, such as reading non-italicized parts of a text (Hopko et al., 1998), or performing a numeric Stroop task in which participants have either to state the quantity of numbers while avoiding interference of numeric identity (i.e., 222222, correct answer, six; Hopko et al., 2002) or the number of greater numerical magnitude while avoiding interference of physical size (i.e., 2 8, correct answer, eight; Suárez-Pellicioni et al., 2014). Finally, the stronger influence of the stimulus-driven attentional system in high anxious individuals is also considered to be at the base of their tendency to preferentially allocate attentional resources to threat-related stimuli, as compared to neutral ones, generating an attentional bias toward this type of information (Eysenck and Byrne, 1992; Eysenck et al., 2007).

Attentional bias toward threat is considered to play an important role in the etiology and maintenance of anxiety disorders (e.g., Williams et al., 1996), by eliciting a "vicious cycle" where attention becomes hypervigilant to all the stimuli related to the person's concerns or worries, which leads to a heightened emotional response (i.e., anxiety reaction). Thus, the greater sensitivity to these concerns would lead the individual to overestimate the level of danger in the environment or the degree of threat, aggravating their emotional disturbance. In this respect, MacLeod et al. (2002) administered medium-trait anxious individuals with a dot probe training procedure[1] in order to establish a general disposition to attend selectively toward or away from emotionally negative information. They found that this attentional bias manipulation modified participants' emotional responses to a stressful situation by influencing the degree to which they selectively processed different aspects of it (MacLeod et al., 2002), giving support to other studies proposing a causal role for attentional bias in anxiety conditions (see for instance Van den Hout et al., 1995).

Attentional bias has traditionally been measured with the emotional Stroop task, in which participants have to report the ink color of threatening (or emotionally charged) and neutral words presented in different ink colors (Williams et al., 1996). The emotional Stroop effect consists of a slower response time to threatening words than to neutral ones, which is considered

[1] In the dot probe task, neutral and threat-related stimuli are presented in the same screen and followed by a probe (a dot) to which the participant have to respond, and which appears either following the threat-related (congruent trials) or the neutral (incongruent trials) stimulus. Thus, while in the classical version of this task the dot appears with the same frequency in each location (i.e., same number of congruent and incongruent trials), in the dot probe training procedure this contingences between stimulus and probe positions are arranged in order to induce a temporary attentional bias either toward or away from threat-related information.

to indicate the allocation of attention to emotional stimuli (processing word content instead of solving the main task of reporting ink color). The emotional Stroop task has been used successfully with patients with panic disorder (Dresler et al., 2012), specific phobia (Wikstrom et al., 2004), social phobia (Andersson et al., 2006), post-traumatic stress disorder (Ashley et al., 2013), generalized anxiety disorder (Mogg and Bradley, 2005), health anxiety (Karademas et al., 2008), etc. In non-clinical populations, the largest emotional Stroop effects are usually observed for those stimuli that relate to the participants' current concerns, such as for dentist-related words for people showing anxiety toward dentist-related situations (Muris et al., 1995) or for cancer-related words in women with family histories of breast cancer (Erblich et al., 2003). Given the early mentioned parallelisms between math anxiety and other types of anxiety, would HMA individuals show an attentional bias as well? Would they be slower to report the ink color of math-related words as compared to neutral ones?

Two studies (Hopko et al., 2002; McLaughlin, unpublished thesis) have already tried to answer this question by means of the emotional Stroop task. First, in a study that used a paper version of the Stroop task including math-related and neutral words, McLaughlin (unpublished thesis) found no increase in response times to math-related words for HMA individuals. However, groups were formed using a split-half subject sample based on the mean math anxiety score, which means that the groups were not representative of extreme high and low math anxiety. Moreover, computer presentations of the task have been shown to be more powerful than the paper-and-pencil format for assessing Stroop-related effects (MacLeod, 1991). Given these methodological limitations, Hopko et al. (2002) decided to form the groups to be extreme on math anxiety scores (top and bottom 20% of their same-gender distribution). Furthermore, they used a computer-based version of the task in which each participant was presented with Stroop screens containing 100 words displayed in five different colors. Despite the authors' efforts to overcome the methodological limitations of the study by McLaughlin (unpublished thesis), they still found no differences in response times, neither between groups nor between types of words. They acknowledged that this might have been due to the type of math-related words they used, which were probably too abstract (e.g., polynomial, theorem) and, therefore, less familiar to HMA individuals, who due to their math avoidance, tend not to enroll in advanced courses. Moreover, response times were calculated for each screen (i.e., 100 words), whereas calculating response times separately for each word would probably have been a more sensitive method.

Within this context, the objective of the present study was to demonstrate an attentional bias toward math-related words in HMA individuals, which would constitute the first step toward further investigation of this bias as a possible mechanism by which math anxiety may originate, be maintained and/or become aggravated. To achieve this objective we took steps to avoid the methodological limitations, which according to Hopko et al. (2002) might have prevented researchers from observing significant results in previous studies. Thus, we formed extreme groups and used a computer-based version of the task. In addition, we presented words individually in order to obtain a more accurate measure of response times, and we used more familiar math-related words. Moreover, we made sure that participants did not differ in trait anxiety, such that any differences between groups could not be explained by this variable. Finally, at the end of the experiment, participants were asked to provide a self-report measure of perceived anxiety to each stimulus.

MATERIALS AND METHODS

Participants

Forty healthy volunteers were tested in this study, half of them with a high level of math anxiety (HMA) and the other half with a low level (LMA). They were selected from among a sample of 629 students from the University of Barcelona who were assessed for math anxiety and trait anxiety (see Materials and Methods) in the context of a larger project.

Participants were selected from the bottom quartile (LMA group) and from the top quartile (HMA group) of the Spanish version of the Abbreviated Mathematics Anxiety Rating Scale (sMARS; Alexander and Martray, 1989) scores. No participant was excluded from the study.

All participants had low scores on the Spanish version of the Zung Self-Rating Depression Scale (Conde et al., 1970; mean = 30.68, *SEM* = 1.03, range = 22–49), indicating that none of them should be classified as depressed.

Groups differed in math anxiety [$t(38) = 19.90$, $p < 0.001$] but not in trait anxiety [$t(38) = 1.12$, $p = 0.26$], depression [$t(38) = 1.24$, $p = 0.22$], age [$t(38) = 0.25$, $p = 0.79$], years of formal education [$t(38) = 1.01$, $p = 0.31$], handedness ($\chi^2 = 0.36$, $p = 0.54$), or ethnicity ($\chi^2 = 1.02$, $p = 0.31$). Groups also differed in gender distribution ($\chi^2 = 7.03$, $p = 0.008$), with more women in the HMA group. More detailed information about the two groups is shown in **Table 1**.

Participants were paid for their participation, gave written informed consent before the experiment and were naïve as to the purposes of the study. All had normal or corrected-to-normal visual acuity and did not report any history of neurological or psychiatric disorders. The experimental protocol was approved by the Ethical Committee of the University of Barcelona.

Materials

Screening Phase

Participants were administered the following instruments:

Shortened Mathematics Anxiety Rating Scale (Alexander and Martray, 1989)

The sMARS is a 25-item version of the Math Anxiety Rating Scale (MARS; Richardson and Suinn, 1972). This instrument measures math anxiety by presenting 25 situations which may cause math anxiety (e.g., *Being given homework assignments of many difficult problems that are due the next class meeting*). Items are answered on a five-point Likert scale, from 1 (no anxiety) to 5 (high anxiety). The possible total score therefore ranges from 25 to 125. The present study used the Spanish version of

TABLE 1 | Means and standard error of the mean (SEM; in brackets) for age, educational level, math anxiety, trait anxiety, and depression and frequencies for gender and manual dominance for the low math-anxious (LMA) and the high math-anxious (HMA) groups.

	Age	Gender	Dominance	Education	sMARS	STAI-T	Depression
LMA	21.95 (0.73)	9	19	9.40 (0.35)	44.95 (1.53)	16.95 (1.53)	29.40 (1.51)
HMA	21.70 (0.63)	17	18	9.90 (0.34)	86.40 (1.31)	20.15 (2.39)	31.95 (1.38)

LMA, low math-anxious; HMA, high math-anxious; Gender, number of females. Dominance: number of right-handed; Education: number of years of formal education counting from 12 years-old forward. sMARS, Abbreviated Math Anxiety Rating Scale; STAI-T, Trait anxiety subscale from the STAI. Depression: Score at the Zung's self-rating depression scale.

the sMARS (Núñez-Peña et al., 2013), which has shown strong internal consistency (Cronbach's alpha = 0.94) and high 7-week test–retest reliability (intra-class correlation coefficient = 0.72).

State-Trait Anxiety Inventory (STAI)

Only the trait anxiety subtest was used. This includes 20 statements describing different emotions. Respondents have to answer by considering how they feel 'in general'. Items are answered on a four-point Likert scale, with options ranging from 0 (almost never) to 3 (almost always). Good to excellent internal consistency (Cronbach's alpha = 0.89–0.96) and adequate 30-day test–retest reliability ($r = 0.75$) have been reported with high-school students (Spielberger et al., 1983). The Spanish version of this test, which has also shown good psychometric properties (Spielberger et al., 2008), was used in this study.

Experimental Session: Pretest

Participants were administered the following scale:

Zung Self-Rating Depression Scale

This scale contains 20 statements. Respondents have to rate the items according to how they apply to him/her over the last few days, using four response options reflecting the frequency of occurrence. Total scores range from 20 to 80, and a score below 49 is considered to indicate no depression. The present study used the Spanish version of this test (Conde et al., 1970), which shows good internal consistency (Cronbach's alpha = 0.79–0.92) and good validity evidence (correlation with the Hamilton and Beck depression scales ranging from 0.50 to 0.80).

Experimental Session: The Emotional Stroop Task

Fourteen neutral words and 14 math-related words were used in the experiment (stimuli are listed in the Appendix). The words were obtained through a questionnaire administered to 117 year-two students from the Faculty of Psychology of the University of Barcelona. This questionnaire asked participants to write down the first 15 words that came to mind when thinking about mathematics. From this information we selected the 14 words that were most reported by students as being math-related. We then selected 14 neutral words from the Spanish lexical database of NIM (Guasch et al., 2013; http://www.bcbl.eu/databases/espal/) that matched the math-related words on several characteristics. Consequently, words in the two categories did not differ in frequency [$t(26) = 0.02$, $p = 0.97$], number of phonemes [$t(26) = 0.08$, $p = 0.93$], familiarity [$t(22) = 0.38$, $p = 0.70$], imageability [$t(22) = 1.04$, $p = 0.30$], or concreteness [$t(22) = 0.71$, $p = 0.48$][2]. **Table 2** shows more detailed information about words characteristics.

The two types of words were presented in separate blocks, that is, a set of math-related words and another set of neutral words. According to Bar-Haim et al.'s (2007) meta-analysis, blocked presentation of stimuli produced a significantly larger combined effect size as compared to randomized presentations (see also Holle et al., 1997). Indeed, the emotional Stroop effect in healthy participants is considered to be a rather slow effect that builds up over subsequent trials (i.e., a carryover effect; McKenna and Sherma, 2004; Phaf and Kan, 2007), the cumulative exposure to threat-related stimuli probably being at the base of stronger perceived threat as compared to randomized presentations. Each block included 58 stimuli: 2 fillers (excluded from the analysis) followed by 56 stimuli corresponding to the 14 words presented in the four ink colors. Stimuli in each block were presented pseudo-randomly, with the only restriction being that the same ink color was never presented in two consecutive trials. Blocks were presented in counterbalanced order and were separated by one minute rest.

The E-prime 2.0 program (Psychology Software Tools Inc., Sharpsburg, PA, USA) was used to control the presentation and timing of the stimuli and the measurement of response accuracy and response times.

Experimental Session: Post-test

At this point, participants were administered the self-report questionnaire, which asked them to rate the level of anxiety generated by each word. There were five response options, ranging from 1 (*Nothing*) to 5 (*A lot*). Participants were told to

[2]The Spanish lexical database defined word frequency as the number of times the word appears in the EsPal corpus divided by the total count of the EsPal corpus words multiplied by one million. Familiarity, imageability and concreteness were assessed by means of the questions: '*How familiar are you with this word on a scale of 1 to 7, with 7 being most familiar?*', '*How imageable is this word on a scale of 1 to 7, with 7 being the most imageable?*', and '*How concrete is this word on a scale of 1 to 7, with 7 being most concrete?*', *respectively.*

TABLE 2 | Mean and standard error of the mean (in brackets) for neutral and math-related words' characteristics.

	Neutral words	Math-related words
Frequency	46.58 (23.05)	47.55 (24.19)
Number of phonemes	8.28 (0.52)	8.35 (0.72)
Familiarity	5.30 (0.16)	5.41 (0.22)
Imageability	4.90 (0.16)	4.54 (0.34)
Concreteness	4.73 (0.09)	4.62 (0.12)

respond by taking into account their thoughts and feelings while performing the emotional Stroop task.

Procedure

Participants were tested individually. Upon entering the experimental room, they completed standard procedures concerning informed consent along with a demographics questionnaire asking their age, manual dominance, gender, and number of years of formal education. Participants were tested individually. After that, they were administered with the Zung's self-rating depression scale (Zung, 1965). Then, participants were given detailed task instructions.

The session began with a training block of 20 words, all of them neutral and different from the ones presented in the experimental session (e.g., Franken et al., 2009). When participants achieved 65% of hits in the training period, the experimental session started. The training trials were only used to familiarize the participants with the task, so they were excluded from the statistical analysis.

Stimuli were presented at the center of a black screen in font type Tahoma (size 35; lowercase) and in four different ink colors (red, blue, green, and yellow). The task for participants consisted in responding to the ink color of the stimuli by means of a button press, as fast and as accurately as possible. Participants responded with the index and middle finger of each hand, using a keyboard and setting their fingers on the response buttons. Response buttons were color-coded with a sticker so that "red", "blue", "green", and "yellow" responses corresponded, respectively, to the letters "d", "f", "j", and "k" on the keyboard. Each trial began with a fixation sign (an asterisk) shown for 500 ms. After that, a word was presented on the screen and remained there until a response was given (maximum of 1500 ms). Each trial was followed by a variable inter-trial interval ranging from 1000 to 1600 ms (a black screen).

DATA ANALYSIS AND RESULTS

Behavioral Measures

Means of response times were calculated for correctly solved trials for each condition and for each participant. Means were calculated after eliminating outliers according to Tukey's method (Tukey, 1977). In this method, extreme outliers are defined as greater or equal to 3 interquartile ranges above the upper quartile (Q3) (i.e., extremely high values) and slower or equal to 3 interquartile ranges below the lower quartile (Q1) (i.e., extremely low values). More concretely, we started by performing boxplots for the response time scores for each participant. Then, we eliminated those values identified as outliers, that is, those that were shown as dots outside the range of the whiskers. Finally, we calculated means of response times for each participant in each condition without the influence of those extreme values. Thus 2.92% of all trials were discarded (2.99% for the LMA group and 2.85% for the HMA one). Percentages of hits were also calculated for each participant in each condition. Response times and percentage of hits were analyzed through analyses of variance (ANOVAs), taking *Stimuli* (math-related word and neutral word) as the within-subject factor and *Group* (LMA and HMA) as the between-subjects factor. The *F* value, the uncorrected degrees of freedom, the probability level following correction, the ε value (when appropriate), and the partial eta square index (η_p^2) are given. We performed tests of simple effects when an interaction was significant, and used the Bonferroni correction to control for the increase in Type I error.

Moreover, a single score of attentional bias was calculated by subtracting the neutral condition from the math-related one, both for response times and for hit rates. For response times, the greater the index, the greater the attentional bias (i.e., more time needed to respond to math-related words than to neutral ones). As for percentage of hits, the slower the index, the greater the attentional bias (i.e., more errors are committed when responding to math-related words than for neutral ones). Student *t*-tests were carried out to compare this index between groups.

Regarding response times, we found a significant main effect of *Group* [$F(1,38) = 4.67$, $p = 0.03$, $\eta_p^2 = 0.11$], with the HMA group being slower than the LMA one. More interestingly, we found a significant *Stimuli* × *Group* interaction [$F(1,38) = 4.28$, $p = 0.04$, $\eta_p^2 = 0.10$]. Simple effects analyses showed that the HMA group took longer to respond to math-related words than to neutral ones [$t(19) = 1.92$, $p = 0.050$, effect size $r = 0.40$], whereas no difference emerged for the LMA group [$t(19) = 0.95$, $p = 0.37$, effect size $r = 0.21$]. On the other hand, when comparing groups for each condition we found that groups differed when responding to math-related words [$t(38) = 2.69$, $p = 0.01$, effect size $r = 0.39$], with the HMA group being slower than the LMA one; however, this group difference was not observed when responding to neutral words [$t(38) = 1.43$, $p = 0.16$, effect size $r = 0.22$]. Moreover, groups differed on the attentional bias index (math-related – neutral) [$t(38) = 2.07$, $p = 0.04$], the HMA group showing greater attentional bias than their LMA peers. Response times for math-related and neutral words (A) and for the attentional bias index (B) for each group are shown in **Figure 1**.

Regarding the percentage of hits, no main effects or interaction reached significance (all *p*-values above 0.25). Similarly, groups did not differ in the attentional bias index [$t(38) = 1.21$, $p = 0.23$]. Means and SEM for response times and percentage of hits for each group and for each stimulus are shown in **Table 3**.

Words' Anxiety Ratings

An ANOVA was performed taking *Stimuli* as the within-subject factor and *Group* as the between-subjects factor. The ANOVA showed a significant *Stimuli* × *Group* interaction [$F(1,38) = 37.23$, $p < 0.001$, $\eta_p^2 = 0.49$]: specifically, the HMA group reported a higher level of anxiety for math-related words as compared with neutral words [$t(19) = 6.28$, $p < 0.001$], whereas no such difference was observed for the LMA group [$t(19) = 0.46$, $p = 0.90$]. When stimuli assessment was compared across groups, they were found to differ for math-related words [$t(38) = 5.86$, $p < 0.001$], but not for neutral words [$t(38) = 0.73$, $p = 0.47$], with the HMA group reporting higher levels of anxiety than the LMA group. In order to be consistent with the analysis of response times and hit rates, a difference score was calculated

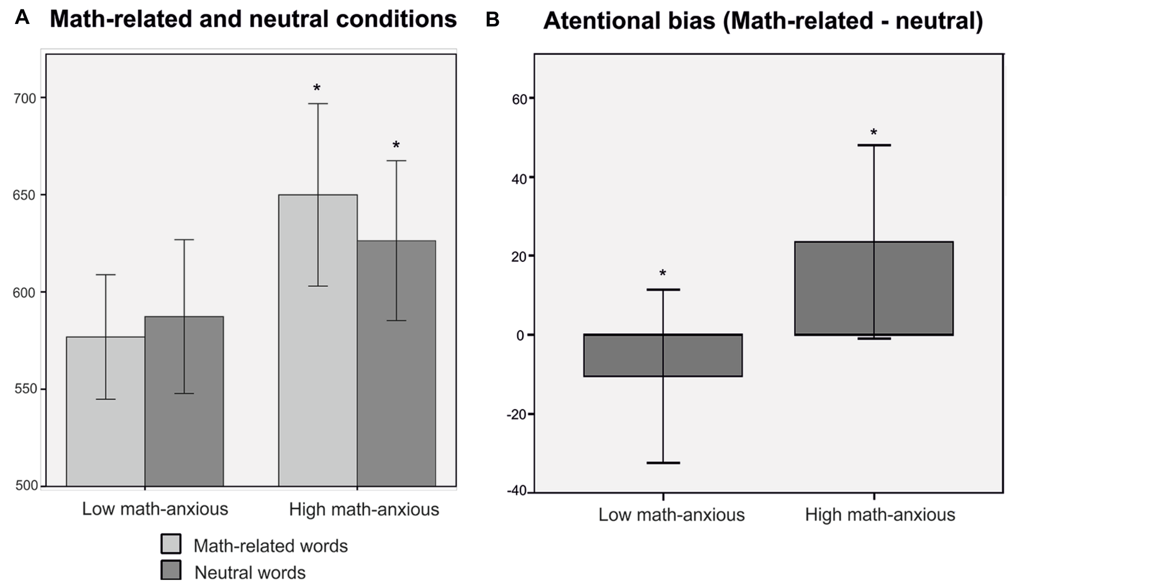

FIGURE 1 | Means and standard errors (in bars) for response times (in ms) for the low math-anxious (LMA) and high math-anxious (HMA) groups when responding to neutral and math-related words (A) and for the attentional bias (B). Significant differences at $^*p < 0.05$.

by subtracting the anxiety reported toward neutral words from the one reported toward math-related ones. This analysis showed that groups differed in this index [$t(38) = 6.10$, $p < 0.001$], showing greater difference for the HMA group than for the LMA one. Means and SEM for these self-reported measures are shown in **Table 3**.

Relationship among Response Times, Words' Anxiety Ratings and Level of Math Anxiety

Participants' levels of math anxiety, trait anxiety, depression and years of formal education were correlated with behavioral (response times and percentage of hits) and self-reported measures to math-related and neutral words, as well as for the attentional bias score (math-related – neutral) in order to further our understanding of the relationship among these variables.

As shown in **Table 4**, results showed significant positive correlations between the sMARS and the time needed to respond to math-related words ($r = 0.38$, $p = 0.01$) and with the math-related words ratings ($r = 0.70$, $p < 0.001$) and for the self-reported difference score ($r = 0.69$, $p < 0.001$). On the contrary, no significant correlations emerged between the sMARS scores and the time needed to respond to neutral words ($r = 0.23$, $p = 0.13$) or with the neutral words ratings ($r = 0.16$, $p = 0.30$).

Interestingly, a positive significant correlation emerged between trait anxiety and behavioral measures, so the higher the level of trait anxiety the slower the response times for both math-related ($r = 0.42$, $p = 0.006$) and neutral ($r = 0.39$, $p = 0.01$) words, and the higher the self-reported measures of anxiety for both math-related ($r = 0.39$, $p = 0.01$) and neutral ($r = 0.40$, $p = 0.008$) words.

As for the relationship between response times and the self-reported level of anxiety generated by words, first, a significant positive correlation emerged between the response times for math-related words and the anxiety ratings for them ($r = 0.47$, $p = 0.002$), so the greater the anxiety reported, the slower the response to them. On the contrary, the time needed to respond to neutral words showed a non-significant correlation with the anxiety ratings for these words ($r = 0.05$, $p = 0.73$). The same positive correlation emerged for the

TABLE 3 | Means of RT (SEM in brackets), percentage of hits and self-reported measures of anxiety for math-related words, neutral words and for their attentional bias index (math-related – neutral) for the LMA and HMA groups.

	LMA			HMA		
	Math-related	**Neutral**	**Attentional bias**	**Math-related**	**Neutral**	**Attentional bias**
RT	576.83 (15.28) •	587.32 (18.89)	−10.48 (10.95) •	649.89 (22.41) ◦ •	626.36 (19.63) ◦	23.52 (12.23) •
Accuracy	94.50 (0.82)	93.14 (0.89)	1.35 (0.90)	93.90 (0.82)	94.00 (0.89)	0.10 (0.89)
Self-reported	15.85 (0.87) •	15.65 (1.00)	0.20 (0.43) •	31.05 (2.44) ◦ •	16.65 (0.92) ◦	14.40 (2.28) •

◦, *Significant differences between conditions;* •, *Significant differences between groups.*

TABLE 4 | Pearson correlation coefficients between subject variables, behavioral (response times and accuracy) and self-reported measures for math-related words, neutral words and their difference (attentional bias) for the whole sample ($n = 40$).

		Subject variables				Response times			Accuracy			Self-reported measures		
		sMARS	**STAI-R**	**Depr**	**Educ level**	**Math**	**Neutral**	**AttBias**	**Math**	**Neutral**	**AttBias**	**Math**	**Neutral**	**AttBias**
Subject variables	sMARS		0.19	0.12	0.10	0.38*	0.23	0.27	−0.03	0.10	−0.14	0.70**	0.16	0.69**
	STAI-R			0.59**	−0.03	0.42**	0.39*	0.08	−0.09	0.04	−0.12	0.39**	0.40**	0.26
	Depr				0.23	0.27	0.12	0.25	−0.08	0.16	−0.24	0.18	0.24	0.09
	Educ level					0.09	0.23	−0.19	−0.06	0.30	−0.36*	0.01	−0.07	0.04
Response times	Math						0.81**	0.40**	−0.50	0.31*	−0.35*	0.47**	0.07	0.48**
	Neutral							−0.20	0.03	0.30	−0.27	0.31*	0.05	0.32*
	AttBias								−0.13	0.04	−0.16	0.30	0.04	0.30*
Accuracy	Math									0.44**	0.46**	−0.15	0.08	−0.20
	Neutral										−0.58**	−0.05	−0.20	0.02
	AttBias											−0.08	0.28	−0.21
Self-reported measures	Math												0.40**	0.92**
	Neutral													0.02
	AttBias													

$*p \leq 0.05$; $**p \leq 0.01$; Depr, Depression; AttBias, math-related – neutral; Accuracy, Percentage of hits.

response times and self-reported difference scores ($r = 0.30$, $p = 0.04$), so the higher the difference in response times (i.e., more time needed to math-related words as compared to neutral ones), the higher the self-reported levels of anxiety generated by math-related words as compared to neutral ones.

DISCUSSION

This study used an emotional Stroop task to investigate the existence of an attentional bias in math anxiety, the aim being to provide evidence for a possible mechanism by which math anxiety may originate, be maintained and/or become aggravated. In order to achieve this objective we designed an experiment that sought to overcome the methodological limitations that previous researchers had suggested that may have prevented them from observing the emotional Stroop effect in HMA individuals. The main methodological improvements were: (1) groups were formed according to extreme scores on math anxiety; (2) we used a computer-based task (like Hopko et al., 2002); (3) words were presented individually; (4) math-related words were carefully selected to be familiar for our sample; (5) several subject variables were controlled for; and (6) self-report measures were included in order to assess perceived anxiety toward each stimulus.

Our results showed that HMA individuals needed longer to report the ink color of math-related words as compared with neutral words, whereas no such difference emerged for their LMA counterparts. This difference shows that participants noticed the meaning of the irrelevant dimension of the task (i.e., stimulus content) and that this math-related content prolonged the time that HMA individuals needed to name the color in which the word was printed, as compared with a neutral one.

Previous research in other types of anxiety had already demonstrated the slow-down in the emotional Stroop task for those words related to the current concerns of the participant or patient. For example, this effect had been found for: physical threat words in panic disorder participants (Dresler et al., 2012), dentist-related words in high dental anxious subjects (Muris et al., 1995), social threat words for social phobics (Andersson et al., 2006), illness-related words in high health anxious individuals (Owens et al., 2004), physical threat words in somatoform patients (Lim and Kim, 2005), threat words (i.e., inept, ashamed) in people who stutter (Hennessey et al., 2014), cancer-related words in women with family histories of breast cancer (Erblich et al., 2003), etc. Our study extends these findings to the field of math anxiety.

However, what lies behind the delay in response times in the emotional Stroop task? Traditionally, the slowdown observed when comparing threatening vs. neutral information has been explained as an *attentional bias* toward threatening or emotional information (Williams et al., 1996). Nevertheless, the mechanisms underlying this attentional bias remain the subject of debate. In this respect, according to the *facilitated attention account*, emotional stimuli are noticed earlier than neutral stimuli (i.e., preferential engagement) and command attention at the expense of other stimuli or dimensions of the stimulus (i.e., ink color; Pratto and John, 1991; Williams et al., 1996). Consequently, the emotional Stroop effect is the product of the disproportionate amount of attention captured by emotional words, attention that would otherwise have been directed to performing the main task (i.e., naming the ink color). The *difficulty in disengagement account*, by contrast, argues that once attention is allocated toward a threat stimulus, it is held longer than in the case of neutral stimuli, thereby disrupting the processing of other stimulus properties and delaying the time needed to report the ink color (Fox et al., 2001).

Unfortunately, the emotional Stroop task does not allow us to distinguish which of these two components of attentional bias is responsible for the observed delay in response times. Thus, it could be the case that HMA individuals showed facilitated attention toward math-related content, such that the word "*fórmula*" (i.e., formula) captured more of their attention than did the word "*calzado*" (i.e., footwear), with the amount of attention that was drawn away from the main task causing the delay in response times. However, it is also possible that HMA individuals showed no preferential engagement but, rather, found it difficult to disengage their attention from math-related information, in which case the word "*fórmula*" would have held attentional resources for longer than did the word "*calzado*", thereby explaining why they needed longer to respond to the former stimulus.

Further research is now needed to determine which of these two alternatives offers the best explanation for attentional bias in HMA individuals. A good option to this aim would be the *dot probe task* (see Rubinsten et al., 2015) in which two stimuli, one threat-related and the other one neutral are presented together in the same screen and their offset is followed by a small probe replacing one of the two stimuli, to which participants are instructed to respond. Trials can be congruent, if the dot replaces threat-related stimuli or incongruent, if the dot replaces a neutral one. One of the main advantages of this task is that, by including a control condition (i.e., two neutral stimuli presented together; Koster et al., 2004), researchers would be able to assess the different subcomponents of attentional bias.

Moreover, it is interesting to note that we found differences between math-anxious groups in a task requiring reporting the ink color of words, that is, a task involving no digits or numerical processing at all. This demonstrates that math anxiety can be raised by several types of stimuli, beyond numbers. In the same line, a previous study, using a novel priming task[3], found that children with developmental dyscalculia (DD) responded faster to arithmetic equations that were presented after negative and math-related words, while the reverse pattern was shown by the control group (Rubinsten and Tannock, 2010). In other words, they found that simple arithmetic problem solving (i.e., addition, subtraction, multiplication and division) was modulated by math-related words (e.g., "quantity") in the same way that in our study this type of words were related with slower response times, as compared with neutral ones, in a task requiring simply to report the ink color of words. In this line, while these two studies have used math-related words, it would be interesting to study math anxiety by means of other stimuli, such as pictures, which show the advantage of having more ecological validity, something that future studies should address.

To summarize, this study constitutes the first evidence showing an attentional bias toward math-related words in HMA individuals by means of an emotional Stroop task. Thus, it seems that Hopko et al. (2002) were right in their assumptions and that previous methodological limitations did prevent researchers from observing significant results in the past, reason why, after improving them, we finally were able to obtain significant differences between groups on attentional bias. Among these improvements, the fact of controlling participants' level of trait anxiety was basic in order to rule out the possibility of general levels of trait anxiety explaining our results. In this respect, correlational analysis showed a very interesting result: while trait anxiety was related with slower response times both to math-related and neutral words, as well to with higher levels of self-reported anxiety toward both types of words, math anxiety showed a specific effect only for math-related words, being related with slower response times and with higher levels of self-reported anxiety toward them, but not relationship with neutral ones.

As commented earlier, this attentional bias toward math-related information may play a role in the origin, maintenance and/or aggravation of math anxiety. In this respect, it has been suggested that differences between low and high anxious individuals have to do with their responsiveness to minor threat cues that do not signal dangers requiring urgent action (Mathews and MacLeod, 2002). Thus, previous literature considers that there is a threat evaluation process in which a certain threshold must be exceeded in order to shift from a mode in which threat-related cues are ignored, to one in which they are attended. In this respect, it has been proposed that a lower threshold level (at which this shift takes place) may be associated with vulnerability to anxiety. Following this idea, it could be the case that children differ in this threshold determining if math-related information is ignored or attended. Thus, those children showing a tendency to easily exceed this threshold and attend to math-related information might be more vulnerable to develop math anxiety. Moreover, this favored attentional processing toward math-related stimuli would make HMA individuals overestimate the level of danger or the degree of threat in the environment (e.g., math class), leading to an increase in their level of math anxiety (i.e., heightened emotional reaction). This increase in their level of math anxiety would, in turn, contribute to a greater tendency to perceive math-related information as threatening, making them even more sensitive to their math concerns.

The fact of having found evidence for an attentional bias in math-anxious individuals can be very useful given that it constitutes the first step in order to set the path for the development of training programs aiming to correct it. For example, it has been shown that only one session of attention bias modification in subjects with social anxiety traits was

[3]In this task, people typically respond to target stimuli more quickly after presentation of an affectively related prime than after one that is unrelated affectively.

sufficient to produce modifications in attention processing and vulnerability toward anxiety (Amir et al., 2009). Given the potential usefulness of investigating attentional bias in HMA individuals, future research deserves to be done in this line, in order to replicate the findings of this study by means of other experimental tasks, by further investigating which components of attentional bias might be mostly affected in HMA individuals and by trying to reveal the role of attentional control in this bias. Then, studies should be focused on proving the effectiveness of an attentional bias modification program in HMA individuals, both for avoiding the aggravation of math anxiety in those children who have started to show evidence of suffering from it, as well as for potentially reducing its negative impact on performance in those adults with a long history of math-anxiety.

ACKNOWLEDGMENTS

We thank Alba Riu, Antonis Filippoussis, Carmen Prieto, and Katherine Huerta for their help with data collection. This study was supported by grants PSI2012-35703 and BES-2010-036859 from the Spanish Ministry of Economy and Competitiveness, and grant SGR2014-177 from the Generalitat de Catalunya.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01577

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 21 August 2015
doi: 10.3389/fpsyg.2015.01268

Processing of multi-digit additions in high math-anxious individuals: psychophysiological evidence

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We investigated the time course of neural processing of multi-digit additions in high- (HMA) and low-math anxious (LMA) individuals. Seventeen HMA and 17 LMA individuals were presented with two-digit additions and were asked to perform a verification task. Behavioral data showed that HMA individuals were slower and more error prone than their LMA peers, and that incorrect solutions were solved more slowly and less accurately than correct ones. Moreover, HMA individuals tended to need more time and commit more errors when having to verify incorrect solutions than correct ones. ERPs time-locked to the presentation of the addends (calculation phase) and to the presentation of the proposed solution (verification phase) were also analyzed. In both phases, a P2 component of larger amplitude was found for HMA individuals than for their LMA peers. Because the P2 component is considered to be a biomarker of the mobilization of attentional resources toward emotionally negative stimuli, these results suggest that HMA individuals may have invested more attentional resources both when processing the addends (calculation phase) and when they had to report whether the proposed solution was correct or not (verification phase), as compared to their LMA peers. Moreover, in the verification phase, LMA individuals showed a larger late positive component (LPC) for incorrect solutions at parietal electrodes than their HMA counterparts. The smaller LPC shown by HMA individuals when verifying incorrect solutions suggests that these solutions may have been appeared more plausible to them than to their LMA counterparts.

Keywords: math anxiety, arithmetic processing, multi-digit additions, ERPs, P2, LPC

OPEN ACCESS

Edited by:
Irene Cristina Mammarella, University of Padova, Italy

Reviewed by:
Sonia White, Queensland University of Technology, Australia
Sara Caviola, University of Padova, Italy

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *16 June 2015*
Accepted: *07 August 2015*
Published: *21 August 2015*

Citation:
Núñez-Peña MI and Suárez-Pellicioni M (2015) Processing of multi-digit additions in high math-anxious individuals: psychophysiological evidence. Front. Psychol. 6:1268. doi: 10.3389/fpsyg.2015.01268

Introduction

In modern-day society, people are heavily dependent on technologies in both their professional and their everyday lives, so it is very important for them to be competent in the STEM (science, technology, engineering, and mathematics) fields. However, the technological advances of recent years have not been accompanied by a corresponding increase in students' mathematical abilities. In fact, a brief look at the latest PISA report (2012 Programme for International Student Assessment) confirms that 15-year old students from many of the Organisation for Economic Co-operation and Development (OECD) member countries have serious difficulties in mathematics (Organisation for Economic Co-operation and Development, 2013). One of the key factors related to math competence is math anxiety, because it has been demonstrated that high math-anxious individuals perform worse than their low math anxious peers on a wide range of numerical and mathematical tasks (Ashcraft et al., 2000; Ashcraft, 2002). Math anxiety is defined as a negative emotional response in situations involving mathematical reasoning that is characterized by avoidance as well as feelings of stress and anxiety (Ashcraft and Faust, 1994; Ashcraft and Ridley, 2005; see Suárez-Pellicioni et al., 2015 for a recent review). This avoidance of math-related situations limits math training in high math anxiety individuals, which in turn negatively affects their math performance and leads to lower grades. Later, when those school-aged children become adults, a low level of math proficiency will reduce their job opportunities and salary prospects (Bynner and Parsons, 1997). Because math anxiety is a problem in today's society, it merits in-depth investigation in order to increase our understanding of the factors contributing to its origin and maintenance.

To date, three accounts have been proposed to explain why high math-anxious individuals (henceforth, HMA) have a poorer performance in mathematics than their low math-anxious peers (henceforth, LMA). First, Ashcraft and colleagues (Ashcraft et al., 2000; Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007) suggested that in HMA individuals a part of the working memory is occupied with worry and intrusive thoughts during performance of numerical task; as a result, they lack sufficient working memory resources to perform the task at hand and their performance deteriorates. The second proposal was formulated some years later by Maloney et al. (2010, 2011) who stated that HMA individuals may have a less precise representation of numerical magnitude, which would compromise the development of more complex math skills. Finally, the third proposal is by Suárez-Pellicioni et al. (2013, 2014), who suggested that HMA individuals have an attentional control deficit which makes them more susceptible to distraction in numerical tasks.

The attentional control theory (Eysenck et al., 2007) explains the relationship between emotion, attention and cognitive performance. This theory proposes that "anxiety affects performance via its adverse effects on attentional control" (Eysenck et al., 2007, p. 170), which is a key function of the central executive component of the working memory (Baddeley, 1986). Specifically, anxiety affects the efficiency of the inhibition function (which uses attentional control to prevent attention being directed to task-irrelevant stimuli and responses) and the shifting function (which uses attentional control in a positive way to respond optimally to changing task requirements). As a consequence, high anxious individuals need to increase the recruitment of any available attentional resources in order to perform the task at hand.

The effects of emotion on attention have been studied in the general population and in both clinical (i.e., anxiety and depression disorders) and non-clinical individuals reporting high levels of anxiety (for a review, see Yiend, 2010). It has been found that emotional material matching individuals' emotional characteristics is attended differently than non-emotional material, and that this effect is similar in clinically anxious and non-clinical high-anxious individuals (Bar-Haim et al., 2007). It has been suggested that the attentional system of anxious individuals may be abnormally sensitive to threat-related stimuli in the environment (Bar-Haim et al., 2005).

Cognitive neuroscientists have used the recording of brain activity at the scalp by means of the event-related brain potential (ERP) technique to study the interaction between attentional and emotional processes (for a review see Hajcak et al., 2010, 2012). ERPs allow for a more direct assessment of these processes than behavioral measures because they obtain an online measure of attentional processing of emotional information. One commonly used component in the study of the effects of emotion on attention is P2, a positive peak with a latency at 200 ms following stimulus onset which is elicited by emotionally negative stimuli (Carretié et al., 2001, 2004). Studies of the P2 component in the clinical population have found that high-anxious participants have greater P2 amplitudes than low-anxious participants when presented with angry faces (Bar-Haim et al., 2005; Eldar et al., 2010). P2 enhancement was also found when less beautiful pendants were presented to a non-clinical population as compared to more beautiful ones (Wang et al., 2012). The increase in P2 amplitude elicited by negative events has been suggested to be a reflection of the mobilization of attentional resources toward emotionally negative stimuli (Carretié et al., 2001; Wang et al., 2012).

In the present study, ERPs were recorded while HMA and LMA individuals performed a multi-digit verification task. This difficult arithmetic task was selected because, according to the attentional control theory (Eysenck et al., 2007), anxiety impairs attentional control, especially during heightened states of anxiety when overall task processing demands are high. Although previous studies have explored single-digit addition solving in LMA and HMA individuals (Suárez-Pellicioni et al., 2013), to the best of our knowledge, no study to date has explored the psychophysiological correlate of more complex addition problem solving in these individuals. Moreover, while in Suárez-Pellicioni et al. (2013) we centered only in the verification of additions, in this study we explored addition solving in a more complete way, by examining early brain activity differences between high- and low-math anxious individuals in both the calculation and verification phases of the arithmetic task. Furthermore, given previous evidence suggesting differences in processing incorrect proposed solutions for simple additions in HMA individuals (Suárez-Pellicioni et al., 2013), the second objective of this study was to examine the verification phase in more depth in order to explore possible group differences when incorrect solutions are presented for a more complex addition task.

As regards behavioral measures, we expected slower response times and lower hit rates in HMA individuals than in their LMA counterparts, because it has been demonstrated that as arithmetic tasks become more complex, the negative effects of anxiety on performance are more evident (Ashcraft and Faust, 1994; Faust et al., 1996). Moreover, we expected incorrect solutions to be solved more slowly and less accurately than correct ones since both solutions showed the same unit number and for incorrect solutions the ten was always one point above the ten in the correct solution (e.g., $27 + 16 = 53$). Thus, incorrect solutions were plausible solutions to the addition and were expected to be more difficult to verify than the correct ones (El Yagoubi et al., 2003;

Núñez-Peña and Escera, 2007). Finally, we expected that the incorrect solutions would appear to be more plausible solutions to HMA than to LMA individuals, given that HMA are expected to have more difficulties with math and to have committed more errors of this type when solving these additions.

As for ERP data, we expected to find different patterns of neural activity in the two groups. Specifically, we expected the multi-digit addition task to mobilize more attentional resources in HMA individuals than in LMA during both the calculation and the verification phases, because multi-digit additions would be emotionally negative stimuli for HMA individuals. As a consequence, we expected a larger P2 component in HMA individuals than in their LMA peers. In addition to these early ERP differences between groups, we also expected differences in the late positive component (LPC) in the verification phase. Previous studies have shown that a LPC with latency around 500 ms post-stimulus and with parietal distribution is elicited whenever an incorrect solution is presented in an arithmetic verification task (Niedeggen et al., 1999; Szucs and Soltész, 2010; Núñez-Peña and Suárez-Pellicioni, 2012). More importantly, differences in the amplitude of this positive component according to arithmetical ability have been found when an incorrect solution very close to the correct one is presented (i.e., a plausible solution such as 9 in the addition 3 + 5), with lower-skilled arithmetic problem-solvers showing a smaller LPC than their higher-skilled counterparts (Núñez-Peña and Suárez-Pellicioni, 2012). This result has been interpreted as an indication of differences in the strength of association between problems and potential solutions depending on arithmetical skills. More specifically, low-skilled individuals are considered to use an exhaustive verification strategy when presented with a plausible incorrect solution because they have been more frequently exposed to this type of error. Thus, the LPC is believed to be a measure of the degree of expectancy or plausibility of the solution presented. In this study, incorrect solutions were expected to elicit a larger LPC in LMA than in HMA individuals, because the latter group, considered to have more difficulties with math, might have higher strength of association between problems and this type of incorrect solutions in their memory, perceiving these incorrect solutions as more plausible than their LMA peers.

Materials and Methods

Participants

Thirty-four healthy volunteers were tested in this study, half of them with a high level of math anxiety (HMA) and the other half with a low level (LMA). Participants were selected from a sample of 629 students of the degree in Psychology at the University of Barcelona who were assessed for math anxiety, trait anxiety and math ability (see Materials and Methods).

The LMA group comprised 17 participants (age range = 19–31, mean = 22.06, standard deviation = 3.54, 16 right-handed) who scored below the first quartile in the Shortened Mathematics Anxiety Rating Scale (sMARS) (Alexander and Martray, 1989) (score range = 30–56, mean = 43.94, standard deviation = 7.36). The HMA group comprised 17 participants (age range = 19–31, mean = 21.94, standard deviation = 2.98, 16 right-handed) who scored above the third quartile in the sMARS (score range = 81–99, mean = 87.41, standard deviation = 5.17).

Groups differed in math anxiety [$t_{(32)} = 19.92$, $p < 0.001$], but not in trait anxiety [$t_{(32)} = 0.87$, $p = 0.39$], age [$t_{(32)} = 0.10$, $p = 0.91$], years of formal education [$t_{(32)} = 1.13$, $p = 0.26$], or handedness ($\chi^2 = 0.00, p = 1$). Differences between groups were found in math ability, showing that HMA individuals correctly solved less additions (mean = 0.16, standard deviation = 0.04) than their LMA peers (mean = 0.21, standard deviation = 0.07) [$t_{(32)} = 2.01$, $p = 0.05$].

All had normal or corrected-to-normal visual acuity and none reported any history of neurological or psychiatric disorders. Participants were naïve as to the purposes of the study and gave written informed consent before the experiment. The experimental protocol was approved by the Ethics Committee of the University of Barcelona and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Material

Shortened Mathematics Anxiety Rating Scale (sMARS) (Alexander and Martray, 1989)

The sMARS is a 25-item version of the Math Anxiety Rating Scale (MARS) (Richardson and Suinn, 1972). This instrument measures anxiety by presenting 25 situations which may cause math anxiety (e.g., *Being given a homework assignment with many difficult problems that are due in the next class meeting*). The participant decides on the level of anxiety associated with the item by providing a score on a five-point Likert scale ranging from 1 (no anxiety) to 5 (high anxiety). The sum of the item scores provides the total score for the instrument, which ranges from 25 to 125. In the present study, we used the Spanish version of the sMARS (Núñez-Peña et al., 2013). The scores for the Spanish version of the sMARS have shown strong internal consistency (Cronbach's alpha = 0.94) and high 7-week test-retest reliability (intra-class correlation coefficient = 0.72).

State-trait Anxiety Inventory (STAI) (Spielberger et al., 1983)

The STAI is a 40-item scale used to measure state (STAI-S) and trait (STAI-T) anxiety. Only the score on the STAI-T was considered in this study, since it reflects a more general and relatively stable tendency to respond with anxiety. This inventory includes 20 statements describing different emotions, and participants answer by considering how they feel "in general." Items are answered on a four-point Likert scale, from 0 (almost never) to 3 (almost always). Good to excellent internal consistency (Cronbach's alpha = 0.95), adequate 30-day test-retest reliability with high school students ($r = 0.75$) and 20-day test-retest reliability with college students ($r = 0.86$) has been reported for the Spanish version of this subscale (Spielberger et al., 2008).

Addition Test from the French Kit (French et al., 1963)

The first page of this test was used to assess participants' math ability. It consists of 60 additions involving three numbers of either one or two digits (e.g., 6 + 67 + 38), vertically presented.

Participants were asked to solve the additions as fast and as accurately as possible during a 2-min period. The number of correctly solved additions over the total of additions presented in the test (i.e., 60) was taken as a measure of participants' arithmetical ability.

Calculation Task

A two-digit addition task was presented to each participant during the recording session. Addends were comprised between 12 and 29 and were presented horizontally on the screen (e.g., 13 + 24). Addends were followed by the proposed solution, which could be correct (e.g., 37) or incorrect (+10 above the correct solution; e.g., 47). From all the possible combinations between the addends mentioned, the ones that could generate confusion with other processes (e.g., rule application) were discarded. More specifically, the numbers 20 and 21 (as well as 10 and 11), tie problems (e.g., 12 + 12) and consecutive addends (e.g., 12 + 13) were not included. From all the remaining possible combinations, 200 additions were randomly selected (the Appendix includes the 100 additions in their smaller + bigger number version). Numbers were presented in font size 50 (Courier New) in white against a black background and at subtended visual angles of 6.30° (addition) or 2.29° (proposed solution), horizontally and 1.48°, vertically.

Procedure

Participants were tested individually. Upon entering the experimental room, participants completed standard procedures for informed consent and a demographics questionnaire asking about their age and number of years of formal education. EEG/EOG sensor electrodes were then attached and participants were given detailed task instructions. Next, participants were seated 100 cm away from the computer screen in an electrically-shielded, sound-attenuating recording chamber. The experimental session began with a training period of 25 trials, on which participants received feedback regarding their performance. The training trials were only used to familiarize the participants with the task and were excluded from the statistical analysis.

The participants' task consisted of indicating whether the proposed solution for the addition displayed was true or false by pressing the left or right button of the mouse. Response buttons were counterbalanced between subjects within each group. Participants were encouraged to answer as fast and as accurately as possible. Each trial began with a fixation sign (an asterisk) shown for 500 ms, which was followed by the addition, presented for 1500 ms with a pre- and post- 100 ms ISI. After this, the proposed solution appeared and remained on the screen until the participant gave a response (or for a maximum of 2000 ms), and then a 500 ms pause was shown. Finally, the trial ended with a variable inter-trial interval ranging from 600 to 900 ms (all pauses consisting of a black screen). The recording session consisted of four blocks of 50 stimuli (200 total trials) separated by a 1-min rest. Trials were randomly presented to each participant. The experiment, including electrode placement and execution of the practice and test phases, lasted about 120 min.

The E-prime 2.0 program (Psychology Software Tools Inc., Sharpsburg, PA, USA) was used to control the presentation and timing of the stimuli and the measurement of response accuracy and response times.

Electrophysiological Recording

The EEG was recorded with ANT hardware and software (B.V., Enschede, The Netherlands) from 64 electrodes positioned according to the extended 10/20 system, as well as two electrodes on the right and left mastoids, and mounted in a commercial WaveGuard EEG Cap (Eemagine Medical Imaging Solutions GmbH. ANT Advanced Neuro Technology). EEG channels were continuously digitized at a rate of 512 Hz by an ANT amplifier (B.V., Enschede, The Netherlands). A band-pass filter was set from 0.16 to 30 Hz, and electrode impedance was kept below 5 kΩ. The horizontal and vertical electrooculogram was recorded with electrodes placed at the outer canthus and below the right eye respectively. The common reference electrode was placed on the tip of the nose, and ground was located at AFz.

Data Analysis

Mean response times (RTs) for correctly solved trials and percentage of hits were calculated for each participant in each condition (correct and incorrect proposed solutions). RTs were calculated after removing trials with values exceeding 2.5 SD from participants' mean scores (outliers) (Van Selst and Jolicoeur, 1994).

Response time and the percentage of hits were analyzed with analyses of variance (ANOVAs) taking *Proposed Solution* (correct, incorrect) as the within-subject factors and *Group* (LMA, HMA) as the between-subjects factor. The *F*-value, the degrees of freedom, the probability level, and the η_p^2 effect size index are given. Whenever an interaction reached significance, simple effect analyses were performed and the Hochberg approach was used to control for the increase in Type I error (Keselman, 1998). Only significant effects ($p \leq 0.05$) are reported.

ERP data time-locked both to the presentation of the two addends (henceforth, the calculation phase) and to the presentation of the proposed solution (henceforth, the verification phase) were then analyzed. Three ERP averages were calculated per participant: one for the calculation phase and two for the verification phase (for correct and incorrect solutions). The averages were constructed from −200 to 800 ms epochs relative to stimulus onset. Trials with voltages exceeding 20 standard deviations in the EOG electrodes and ±100 μV in the remaining electrodes were excluded from the ERP average. Ocular artifacts were identified and corrected with the eye-movement correction algorithm used in the EEprobe program (ANT, The Netherlands).

For the ERP analysis of the calculation phase, ANOVAs were performed on the ERP mean amplitudes in the 175–225 ms window in order to study the P2 component. Analysis was performed at nine electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4), taking *Frontality* (frontal, central, parietal), and *Laterality* (three levels from left to right) as within-subject factors and *Group* (LMA, HMA) as the between-subjects factor. For the ERP analysis of the verification phase, ANOVAs were performed on the ERP mean amplitudes in the 175–225 ms window in order to study the P2 component and in the 400–600 ms window in order to study the LPC. The *F*-value, the uncorrected degrees of freedom, the probability level following correction, the ε-value (when appropriate), and the η_p^2 effect size index are given. Whenever an interaction reached significance, simple effect analyses were performed and the Hochberg approach was used to control for the increase in Type I error (Keselman, 1998). Only significant effects ($p \leq 0.05$) are reported.

Results

Behavioral Results

As far as response time was concerned, the main effects of Proposed solution [$F_{(1, 32)} = 48.44$, $p < 0.001$, $\eta_p^2 = 0.60$] and Group [$F_{(1, 32)} = 6.36$, $p = 0.01$, $\eta_p^2 = 0.16$] reached statistical significance. Incorrect proposed solution were verified more slowly (mean = 766.55 ms, SEM = 35.48 ms) than correct proposed solutions (mean = 694.32 ms, SEM = 32.44 ms), and HMA individuals were slower (mean = 815.20 ms, SEM = 47.51 ms) than their LMA peers (mean = 645.67 ms, SEM = 47.51 ms). More interestingly, the Proposed solution x Group interaction was marginally significant [$F_{(1,32)} = 3.69$, $p = 0.06$, $\eta_p^2 = 0.10$]. This interaction showed that the difference between incorrect and correct solutions was larger for the HMA (mean = 92.2 ms, SEM = 17.5) than for the LMA (mean = 52.3 ms, SEM = 11.1) group, [$t_{(32)} = 1.92$, $p = 0.06$]. Means and standard errors of response times for correct and incorrect proposed solutions for the LMA and HMA groups are given in **Table 1**.

As for the percentage of hits, the main effects of Proposed solution [$F_{(1, 32)} = 18.12$, $p < 0.001$, $\eta_p^2 = 0.36$] and Group [$F_{(1, 32)} = 7.84$, $p = 0.009$, $\eta_p^2 = 0.19$] reached statistical significance. Incorrect proposed solutions were verified less accurately (mean = 83.9, SEM = 1.9) than correct proposed solutions (mean = 88.9, SEM = 1.1), and HMA individuals made fewer hits (mean = 82.3, SEM = 2.1) than their LMA peers (mean = 90.4, SEM = 2.1). The analysis of the differences in percentage of hits between correct and incorrect solutions revealed a marginally significant effect of Group [$F_{(1, 32)} = 3.455$, $p = 0.07$, $\eta_p^2 = 0.10$], showing that the decrease in percentage of hits from correct to incorrect solutions was larger in the HMA group (mean = −12.9, SEM = 2.3) than in the LMA group (mean = −6.9, SEM = 2.3). Means and standard errors of percentage of hits for correct and incorrect proposed solutions for the LMA and HMA groups are given in **Table 1**.

TABLE 1 | Means of response times (in ms) and of percentage of hits (standard error of the mean in brackets) for correct and incorrect proposed solutions for the LMA and HMA groups.

	Response times		Percentage of hits	
	Incorrect	Correct	Incorrect	Correct
LMA	671.82 (41.86)	619.53 (40.23)	88.29 (2.69)	92.68 (1.63)
HMA	861.29 (57.30)	769.12 (50.90)	79.52 (2.69)	85.06 (1.63)

LMA, Low math-anxious group; HMA, High math-anxious group.

ERP Results: Calculation Phase

Figure 1A shows the grand-average ERPs for each group in the calculation phase at frontal, central and parietal electrodes. The differences between groups were evident at about 200 ms post-stimulus, where HMA individuals showed a larger P2 component than their LMA peers. Scalp topographic maps in **Figure 1B** reveal brain activity in the 175–225 ms window for both groups; they show that the positive component was larger in the HMA group than in the LMA group and that this P2 component was widely distributed. Topographic maps were plotted using the EEProbe 3.1 program (ANT Software BV, Enschede, The Netherlands).

The statistical analysis performed on the 175–225 ms window supports these observations. The overall ANOVA revealed a significant effect of Group [$F_{(1, 32)} = 6.72$, $p = 0.014$, $\eta_p^2 = 0.17$] showing that voltage was more positive for HMA individuals (mean = 5.9, SEM = 0.6) than for their LMA counterparts (mean = 3.5, SEM = 0.6). None of the interactions with the Group factor reached significance. **Table 2** shows amplitude means and standard errors for both groups in all the electrodes analyzed.

ERP Results: Verification Phase

Figure 2A shows the grand-average ERPs for each group in the verification phase for correct proposed solutions at frontal, central and parietal electrodes. The differences between groups were evident at about 200 ms post-stimulus, when HMA individuals showed a larger P2 component than their LMA peers. Differences between groups were also evident later, when the LMA group showed a larger LPC, peaking about 400 ms post-stimulus compared with their HMA counterparts. This effect was larger at parietal positions. Scalp topographic maps in **Figures 2B,C** show brain activity in the 175–225 and the 400–600 ms windows for both groups. **Figure 2B** reveals that the P2 component was frontocentrally distributed and was larger in the HMA group than in LMA. **Figure 2C** shows that the LPC was parietally distributed and was larger in the LMA group than in HMA.

Figure 3A shows the grand-average ERPs for each group in the verification phase for incorrect proposed solutions at frontal, central and parietal electrodes. **Figures 3B,C** showed scalp topographic maps for the P2 and the LPC for both groups in incorrect proposed solutions. For these components, these figures showed ERP patterns similar to the ones described above for correct solutions.

The ANOVA performed on the 175–225 ms window revealed a significant main effect of Group [$F_{(1, 32)} = 15.01$, $p < 0.001$, $\eta_p^2 = 0.32$], showing that voltage was more positive for HMA individuals (mean = 4.2, SEM = 0.4) than for their LMA counterparts (mean = 1.9, SEM = 0.4). None of the interactions with the Group factor reached statistical significance.

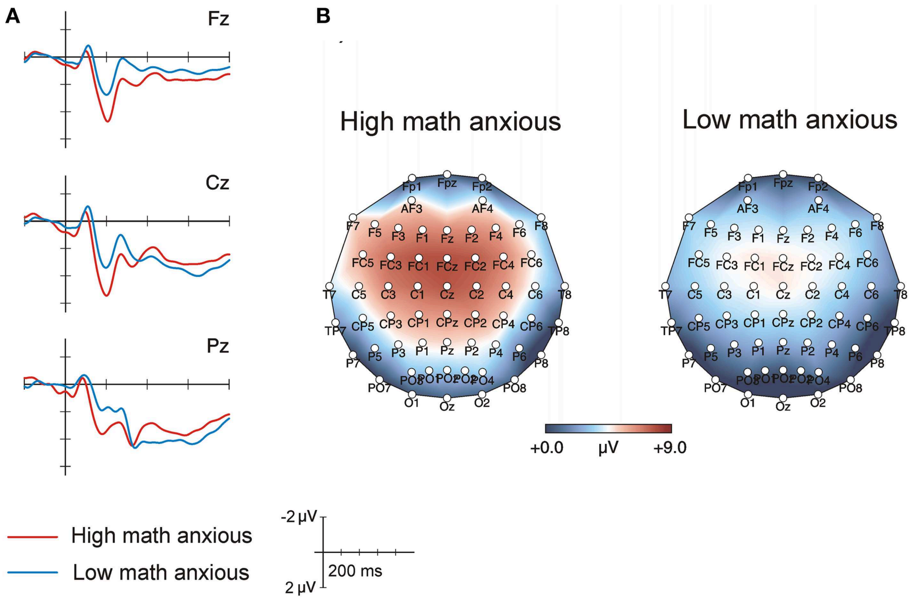

FIGURE 1 | (A) Raw averaged waveforms for HMA ($n = 17$) and LMA ($n = 17$) individuals during the calculation phase. **(B)** Topographic maps waveforms for HMA and LMA individuals in the 175–225 ms window of the calculation phase.

TABLE 2 | Mean amplitudes (in µV) and standard error (in brackets) for the P2 component in the calculation phase (175–225 ms) for the HMA and LMA groups.

	F3	Fz	F4	C3	Cz	C4	P3	Pz	P4
HMA	6.28 (0.54)	6.61 (0.57)	6.17 (0.54)	6.91 (0.72)	7.78 (0.84)	6.27 (0.78)	4.34 (0.76)	5.09 (0.94)	4.18 (0.90)
LMA	3.94 (0.54)	3.90 (0.57)	3.91 (0.54)	4.27 (0.72)	4.81 (0.84)	3.73 (0.78)	2.27 (0.76)	2.65 (0.94)	2.10 (0.90)

Moreover, neither the main effect of Proposed solution nor any of the interactions with this factor were significant. **Table 3** shows amplitude means and standard errors for both groups in all the electrodes analyzed.

As for the ANOVA performed on the 400–600 ms window, the interactions Group × Frontality [$F_{(2,\ 64)} = 4.98$, $p = 0.01$, $\varepsilon = 0.14$, $\eta_p^2 = 0.22$] and Proposed solution × Frontality, [$F_{(1,\ 64)} = 3.54$, $p = 0.04$, $\varepsilon = 0.69$, $\eta_p^2 = 0.10$] were statistically significant. Separate follow-up ANOVAs were computed for each level of frontality, showing that the Group effect [$F_{(1,\ 32)} = 3.69$, $p = 0.06$, $\eta_p^2 = 0.10$] and the Group x Proposed solution interaction were marginally significant at parietal positions [$F_{(1,\ 32)} = 3.43$, $p = 0.07$, $\eta_p^2 = 0.09$]. In order to study this interaction in more detail, simple effects analysis was performed and results showed that amplitude was more positive for LMA individuals (mean = 5.6, SEM = 0.8) than for their HMA peers (mean = 3.1, SEM = 0.8) at parietal sites for incorrect solutions [$F_{(1,\ 32)} = 4.9$, $p = 0.03$, $\eta_p^2 = 0.13$] but not for the correct ones, which showed no differences between groups. No significant effects were found at frontal and central positions. **Table 4** shows amplitude means and standard errors for both groups for correct and incorrect solutions in all the electrodes analyzed.

Discussion

The present study examined the behavioral and electrophysiological measures of HMA and LMA individuals when performing a multi-digit addition verification task, by focusing on both the calculation and the verification phases. To our knowledge this is the first time that multi-digit addition processing has been studied in HMA individuals by means of the ERP technique. Our objective was two-fold. First, we were interested in studying attentional processes. According to the attentional control theory (Eysenck et al., 2007), we expected that HMA individuals would need to allocate more attentional resources to perform the arithmetical task than their LMA counterparts, because they would perceive multi-digit additions as emotionally negative stimuli. Therefore, we expected larger P2 amplitudes in math-anxious participants. Second, we aimed to study differences in the processing of incorrect solutions between the two groups. Specifically, we expected to find between-group differences in the amplitude of the LPC, a component whose amplitude increases with the implausibility of the solution presented in an arithmetic verification task (Niedeggen et al., 1999; Szucs and Soltész, 2010; Núñez-Peña and Suárez-Pellicioni, 2012). In the present study, incorrect solutions were expected to

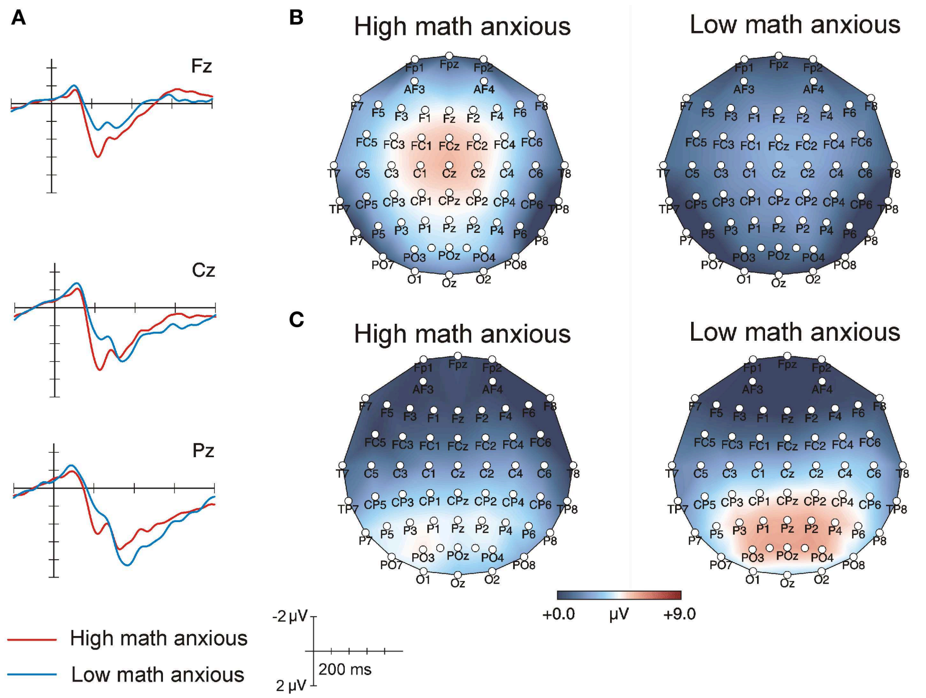

FIGURE 2 | (A) Raw averaged waveforms for HMA ($n = 17$) and LMA ($n = 17$) individuals during the verification phase when correct solutions were presented. **(B)** Topographic maps for HMA and LMA individuals in the 175–225 ms window of the verification phase. **(C)** Topographic maps for HMA and LMA individuals in the 400–600 ms window of the verification phase.

appear more plausible to HMA than to LMA individuals, because the former would have committed more errors of this type, so the association between the addition and the incorrect solution would be stronger for them. Therefore, using ERP methodology, we expected LMA individuals to show a larger LPC for incorrect proposed solutions than their HMA peers.

The behavioral results of the study partially confirmed our predictions. Regarding behavioral measures, HMA individuals were slower and more error prone than their LMA counterparts. This result was expected because math anxiety and math competence have shown a consistent, negative relationship (Ashcraft and Ridley, 2005). Moreover, correct solutions were solved faster and more accurately than incorrect ones. This result was also expected because incorrect solutions were constructed by adding 10 to the correct solution, being, therefore, plausible solutions requiring participants to check the tens. Finally, as for the analyses of the difference scores in percentage of hits and response time, we found that the decrease in percentage of hits and increase in response times from correct to incorrect solutions tended to be larger in the HMA group than in the LMA group. This result suggests that as we had predicted, incorrect solutions seemed to be more plausible to the HMA group as compared to their LMA peers. However, differences between groups were marginally significant (p-values of 0.06 and 0.07 for response times and hit rates, respectively) and effect sizes were low (η_p^2 of 0.1 for both measures), so these effects need further investigation.

With regard to electrophysiological measures, our data revealed two relevant results. First, between-group differences were found at about 200 ms post-stimulus in both the calculation and the verification phases of the arithmetic task. Specifically, HMA individuals presented greater P2 amplitude than their LMA peers. Because increased P2 amplitude is elicited in response to stimuli arousing negative feelings and is considered to be an indicator of the mobilization of attentional resources to the stimulus processing (Carretié et al., 2001, 2004), the present findings suggest that HMA individuals needed to invest more attentional recourses to perform the arithmetic task than their LMA peers. Moreover, the fact that this effect was present in both the calculation and verification phases provides evidence that it is a very robust effect and that the stronger mobilization of attentional resources in HMA individuals was needed not only in the initial step of the calculation process (when both addends are presented in the calculation phase) but also in the final step of the verification process (when the proposed solution is presented). However, although HMA individuals invested more attentional resources, they still needed more time and committed more errors when solving the verification task. In line with the attentional control theory (Eysenck et al., 2007), this finding suggests that HMA individuals not only showed differences in what Eysenck et al. called *performance effectiveness*, that is, in their level of performance on the task (behavioral measures), but also in *processing efficiency*, given that using more resources (P2 amplitude) to achieve their level of performance made their processing less efficient.

The second psychophysiological result in the present study is that between-group differences were also found for incorrect

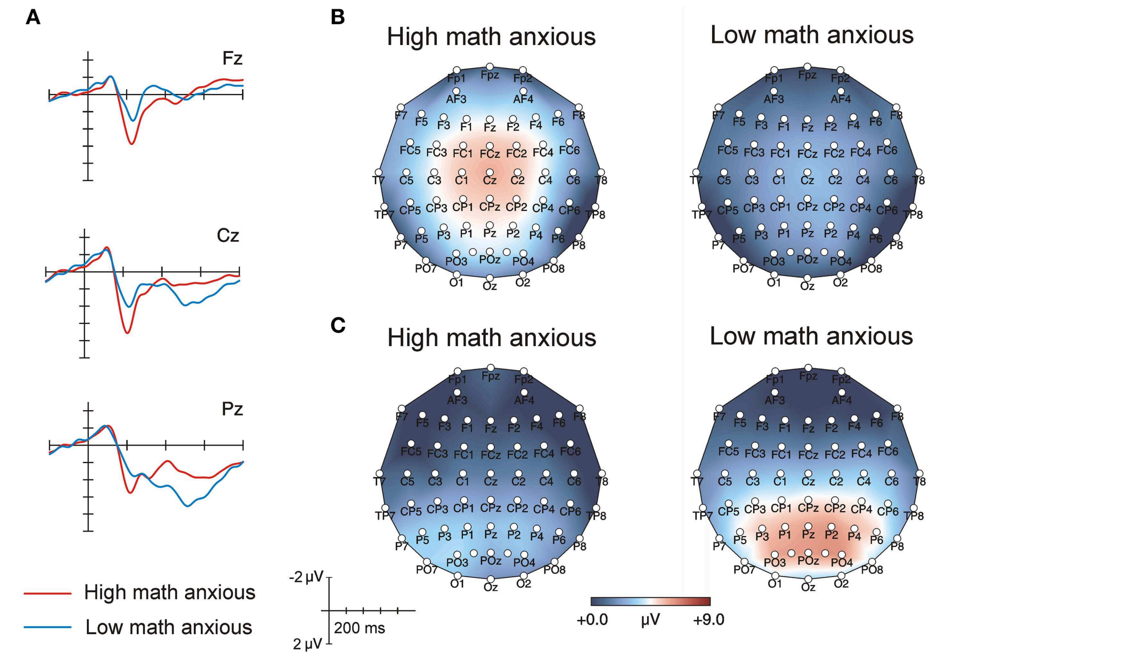

FIGURE 3 | (A) Raw averaged waveforms for HMA ($n = 17$) and LMA ($n = 17$) individuals during the verification phase when incorrect solutions were presented. **(B)** Topographic maps for HMA and LMA individuals in the 175–225 ms window of the verification phase. **(C)** Topographic maps for HMA and LMA individuals in the 400–600 ms window of the verification phase.

proposed solutions in the verification phase. These differences emerged at a late stage of processing: a LPC with latency about 500 ms post-stimulus showed a larger amplitude for LMA than for HMA individuals at parietal electrodes. Previous research has shown that whenever an incorrect solution is presented in an arithmetic verification task, a parietal LPC is elicited and its amplitude is modulated by the distance between the correct and the incorrect proposed solution (Niedeggen et al., 1999; Szucs and Csépe, 2004, 2005; Núñez-Peña and Escera, 2007; Szucs and Soltész, 2010). In addition, Núñez-Peña and Suárez-Pellicioni (2012) found a modulation in the LPC amplitude depending on arithmetical ability, reporting a smaller LPC for lower-skilled individuals. Since LPC amplitude is taken as an indicator of the plausibility of the solution, they suggested that incorrect solutions close to the correct ones appear to be more plausible to low-skilled individuals than to their high-skilled peers.

Our result concerning the LPC differences between groups can be explained in terms of the degree of plausibility of the proposed incorrect solution for high- and low-math anxious individuals. In our study, we created incorrect solutions by adding 10 to the correct solution, so that participants needed to calculate the tens in order to correctly verify the additions. In this way, our incorrect solutions were plausible solutions for the addition at hand. The fact that a reduction in the amplitude of this component was shown in HMA individuals for incorrect solutions suggests that these solutions were more plausible to them than to their LMA counterparts. This difference may be due to the fact that, in line with the well-known negative correlation between math anxiety and math competence (Hembree, 1990), HMA individuals would have been less skilled than their LMA peers. The present interpretation of this result is also in accordance with our behavioral results, which showed that the increase in RTs and the decrease in hit rates for incorrect solutions compared with the correct ones tended to be larger for HMA individuals.

As a whole, one of the main implications of this study is that it is the first one finding an enhanced P2 component in math anxiety, suggesting that numbers may have generated an emotionally negative response in HMA individuals, in the same way as other stimuli generated the same response in other anxious populations (e.g., angry faces; Eldar et al., 2010). Moreover, the results of this study can better be explained by one of the three accounts that explain the negative effects of math anxiety on performance. In line with Ashcraft and colleagues' account (Ashcraft et al., 2000; Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007), HMA individuals would have experienced intrusive thoughts regarding the math task (e.g., doubts about being able to perform well, etc.) so, in order to compensate for this detrimental effect of math anxiety, HMA individuals may have increased their attentional resources (cognitive effort), which would have been reflected in the increase on the P2 component. However, even with this effort, they still performed worse (were slower and made fewer hits) than their LMA peers.

In conclusion, this study has been the first in demonstrating that HMA individuals show larger amplitudes of the attention-related P2 ERP component than their LMA counterparts when performing a two-digit addition verification task. This is a very

TABLE 3 | Mean amplitudes (in μV) and standard error (in brackets) for the P2 component in the verification phase (175–225 ms) for the HMA and LMA groups.

	F3	Fz	F4	C3	Cz	C4	P3	Pz	P4
HMA	3.64 (0.39)	4.42 (0.41)	3.78 (0.43)	4.49 (0.51)	5.80 (0.52)	4.11 (0.50)	3.90 (0.54)	4.53 (0.59)	3.58 (0.53)
LMA	1.39 (0.39)	1.85 (0.41)	1.59 (0.43)	1.87 (0.51)	2.84 (0.52)	2.13 (0.50)	1.55 (0.54)	2.18 (0.59)	1.68 (0.53)

TABLE 4 | Mean amplitudes (in μV) and standard error (in brackets) for the LPC component in the verification phase (400–600 ms) for the HMA and LMA groups.

	F3	Fz	F4	C3	Cz	C4	P3	Pz	P4
CORRECT SOLUTIONS									
HMA	0.03 (0.66)	0.22 (0.66)	0.27 (0.70)	1.26 (0.72)	1.89 (0.87)	2.29 (0.71)	4.33 (0.67)	4.22 (0.74)	4.05 (0.67)
LMA	−0.18 (0.66)	−0.27 (0.66)	0.22 (0.70)	2.48 (0.72)	2.74 (0.87)	3.44 (0.71)	5.23 (0.67)	5.74 (0.74)	5.41 (0.67)
INCORRECT SOLUTIONS									
HMA	−0.02 (0.80)	0.17 (0.83)	−0.19 (0.85)	0.71 (0.91)	1.34 (1.04)	1.34 (0.88)	3.34 (0.85)	3.06 (0.91)	2.84 (0.78)
LMA	0.32 (0.80)	0.09 (0.83)	0.07 (0.85)	2.74 (0.91)	2.94 (1.04)	3.27 (0.88)	5.32 (0.85)	6.04 (0.91)	5.57 (0.78)

robust effect because P2 differences between groups were found when both addends were presented (the calculation phase) and also when the proposed solution was presented (the verification phase). These findings may suggest that a complex arithmetic task elicited greater mobilization of attentional resources in HMA than in LMA individuals, probably because such a numeric task elicited a negative emotional response in those individuals high in anxiety toward math. Moreover, the larger LPC amplitude found for HMA individuals in incorrect proposed solutions might indicate that this type of solution appears to be more plausible to them than to their LMA peers, due to the fact that they would have committed more errors of this type when solving additions. Despite the relevant results raised by this study, a limitation should be acknowledged that has to do with the natural relationship between math anxiety and math ability, an association that posits difficulties in order to study math anxiety, given that the effects of math ability would always be, somehow, intervening in explaining the effects found.

Funding

This research was supported by the Spanish Ministry of Economy and Competitiveness under grant PSI2012-35703, the Spanish Ministry of Science and Technology under grant BES-2010-036859, and the Generalitat de Catalunya under grant SGR2014-177.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix

Addition	Correct	Incorrect	Addition	Correct	Incorrect	Addition	Correct	Incorrect
12 + 14	26	36	16 + 23	39	49	24 + 16	40	50
12 + 17	29	39	16 + 25	41	51	24 + 19	43	53
12 + 19	31	41	16 + 29	45	55	24 + 22	46	56
12 + 23	35	45	17 + 12	29	39	24 + 23	47	57
12 + 25	37	47	17 + 14	31	41	24 + 28	52	62
12 + 27	39	49	17 + 22	39	49	25 + 12	37	47
13 + 12	25	35	17 + 25	42	52	25 + 13	38	48
13 + 15	28	38	17 + 26	43	53	25 + 14	39	49
13 + 19	32	42	17 + 29	46	56	25 + 16	41	51
13 + 22	35	45	18 + 14	32	42	25 + 19	44	54
13 + 24	37	47	18 + 23	41	51	25 + 22	47	57
13 + 26	39	49	18 + 25	43	53	25 + 28	53	63
13 + 27	40	50	18 + 29	47	57	26 + 12	38	48
13 + 29	42	52	19 + 1 2	31	41	26 + 13	39	49
14 + 12	26	36	19 + 23	42	52	26 + 15	41	51
14 + 17	31	41	19 + 29	48	58	26 + 19	45	55
14 + 19	33	43	22 + 12	34	44	26 + 22	48	58
14 + 22	36	46	22 + 14	36	46	26 + 23	49	59
14 + 23	37	47	22 + 17	39	49	26 + 28	54	64
14 + 24	38	48	22 + 18	40	50	27 + 12	39	49
14 + 25	39	49	22 + 19	41	51	27 + 13	40	50
14 + 28	42	52	22 + 24	46	56	27 + 16	43	53
15 + 12	27	37	22 + 27	49	59	27 + 18	45	55
15 + 13	28	38	22 + 29	51	61	27 + 22	49	59
15 + 14	29	39	23 + 12	35	45	28 + 12	40	50
15 + 17	32	42	23 + 14	37	47	28 + 15	43	53
15 + 22	37	47	23 + 16	39	49	28 + 18	46	56
15 + 24	39	49	23 + 18	41	51	28 + 26	54	64
15 + 26	41	51	23 + 19	42	52	29 + 12	41	51
15 + 29	44	54	23 + 22	45	55	29 + 15	44	54
16 + 12	28	38	23 + 26	49	59	29 + 23	52	62
16 + 13	29	39	23 + 29	52	62	29 + 27	56	66
16 + 18	34	44	24 + 12	36	46			
16 + 22	38	48	24 + 15	39	49			

frontiers in Psychology

ORIGINAL RESEARCH
published: 02 February 2016
doi: 10.3389/fpsyg.2016.00042

Mathematics Anxiety, Working Memory, and Mathematics Performance in Secondary-School Children

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Mathematics anxiety (MA) has been defined as "a feeling of tension and anxiety that interferes with the manipulation of numbers and the solving of math problems in a wide variety of ordinary life and academic situations." Previous studies have suggested that a notable proportion of children in primary and secondary school suffer from MA, which is negatively correlated with calculation skills. The processing efficiency and attentional control theories suggest that working memory (WM) also plays an important part in such anxious feelings. The present study aimed to analyze the academic achievement and cognitive profiles of students with high math anxiety (HMA) and low math anxiety (LMA). Specifically, 32 students with HMA and 34 with LMA matched for age, gender, generalized anxiety, and vocabulary attending sixth to eighth grades were selected from a larger sample. The two groups were tested on reading decoding, reading comprehension, mathematics achievement, and on verbal short-term memory and WM. Our findings showed that HMA students were weak in several measures of mathematics achievement, but not in reading and writing skills, and that students with HMA reported lower scores on short-term memory and WM performances (with associated difficulties in inhibiting irrelevant information) than children with LMA. In addition, a logistic regression showed that weaknesses in inhibitory control and fact retrieval were the strongest variables for classifying children as having HMA or LMA.

Keywords: mathematics anxiety, short-term memory, working memory, inhibitory control

OPEN ACCESS

Edited by:
Bernhard Hommel,
Leiden University, Netherlands

Reviewed by:
Sarah Wu,
University of Colorado, Boulder, USA
Carla Colomer,
Universidad Jaume I de Castellón, Spain

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *24 June 2015*
Accepted: *11 January 2016*
Published: *02 February 2016*

Citation:
Passolunghi MC, Caviola S, De Agostini R, Perin C and Mammarella IC (2016) Mathematics Anxiety, Working Memory, and Mathematics Performance in Secondary-School Children. Front. Psychol. 7:42. doi: 10.3389/fpsyg.2016.00042

INTRODUCTION

Mathematical difficulties may be seen not only in children with specific mathematical learning disorders, but also in those with emotional issues, such as mathematics anxiety (MA) (Ashcraft and Kirk, 2001; Maloney and Beilock, 2012; Vukovic et al., 2013). Previous studies have shown that individuals with MA have increasing difficulty the greater the demand of the mathematical problem (Ashcraft and Moore, 2009). A negative loop is generated in which these individuals often perform badly in standardized math tests (Hembree, 1990; Ashcraft and Krause, 2007), avoid arithmetic courses (Hembree, 1990; Ashcraft and Moore, 2009), and develop negative beliefs regarding their own math abilities (Lent et al., 1991; Ashcraft and Kirk, 2001), thus experiencing even more MA and avoidance. Given the long-term damaging effects of MA, it is important to understand how MA affects mathematics achievement.

Mathematics builds on several cognitive abilities (Passolunghi et al., 2008; Krajewski and Schneider, 2009; Geary, 2011) implemented by an extensive neural network in the brain (Goswami and Szűcs, 2011; Fias et al., 2013), and influenced by emotional aspects (such as feelings of apprehension, dislike, tension, worry, frustration, and fear) experienced when performing mathematical tasks, which goes by the name of mathematics anxiety. On the relationship between MA and cognitive processes, previous studies have shown that individuals with a limited working memory (WM) capacity may experience difficulty in regulating their anxiety levels (Hofmann et al., 2011), and anxiety/worry may reduce their WM resources (Eysenck et al., 2007; Mammarella et al., 2015). It is common knowledge that cognitive skills such as WM, processing speed, attention and inhibition are important in the setting of mathematical learning difficulties (Fletcher et al., 2007). The cognitive consequences of MA have also been characterized in several studies, which have associated MA with an impaired WM and attention capacity (e.g., Ramirez et al., 2013).

Theories on processing efficiency and attentional control suggest an important role for WM in regulating cognitive performances (Eysenck and Calvo, 1992; Richards and Gross, 2000; Eysenck et al., 2007). According to processing efficiency theory and attentional control theory (ACT), worrying (which is the cognitive component of anxiety) is believed to demand processing competence, thereby reducing the WM capacity available for other tasks (Eysenck and Calvo, 1992; Ashcraft and Kirk, 2001; Derakshan and Eysenck, 2009; Eysenck and Derakshan, 2011). In particular, the ACT approach (Eysenck and Calvo, 1992) assumes that anxiety interferes with the efficient functioning of the goal-directed attentional system, as well as reducing attentional control; in other words, anxiety raises an individual's attention to threat-related stimuli. According to the ACT approach, the negative effects of anxiety on processing efficiency would therefore stem from two executive functions involving attentional control: inhibition and shifting (Eysenck et al., 2007). That does not mean that the quality of an individual's performance (as usually assessed by means of standard behavioral measures such as response accuracy) is necessarily impaired, especially if their anxiety prompts the use of compensatory strategies (e.g., more effort, or a greater use of processing resources).

The complexity of the interaction between cognition and emotion also depends on the difficulty of the arithmetical tasks proposed. For instance, in investigating the effects of WM on emotion regulation, different arithmetical tasks have been used to manipulate the load on WM (Van Dillen and Koole, 2009; Van Dillen et al., 2009; Kanske et al., 2011), and math-specific anxiety has been associated with a reduced WM capacity and with a slow and inaccurate handling of arithmetical problems (Ashcraft and Faust, 1994; Ashcraft and Kirk, 2001; Mattarella-Micke et al., 2011; Suárez-Pellicioni et al., 2013). Interactions between negative emotion and WM capacity have also been shown to affect more complex math problem solving and reasoning abilities (Owens et al., 2014). In particular, Owens et al. (2014) found that high levels of anxiety negatively affected math reasoning in individuals with relatively small digit and spatial spans, whereas they positively affected reasoning ability in those with a high WM span.

Surprisingly little is known about the specific detrimental effect of MA on academic achievement in middle school students. Most previous studies were conducted on young adults, or children in the early stage of math learning (Wu et al., 2012; Ramirez et al., 2013), while few studies have included participants of middle school by studying the relationship between MA and algebraic problem solving in 14 years-old (Trezise and Reeve, 2014, 2015). The present study, aimed to investigate the relationship between MA and mathematical achievement in a group of middle school students (in grades six to eight) in order to fill the gap of the previous literature. In addition, we aimed to look into: how specifically the detrimental effect of MA concerned math achievement, but not reading and writing achievement; and the relationship between MA and WM, also considering the role of inhibitory processes at this particular developmental age.

The present study was therefore designed to investigate whether (a) different patterns of mathematical abilities emerge in two groups of middle school students selected on the basis of their level of MA (but matched for general anxiety); (b) students with high or low levels of MA were also impaired in different areas of academic achievement, such as reading decoding, reading comprehension and writing abilities; (c) the two groups of students performed differently in measures of verbal short-term memory and WM; (d) different levels of MA were associated with the ability to inhibit irrelevant information. Finally, (e) in the present research, the variables able to identify children with high and low MA were also analyzed. To investigate these issues, we used a similar paradigm to the one employed by Passolunghi (2011) and Passolunghi and Siegel (2001, 2004), with an exception regarding the groups' selection. In a previous study, Passolunghi (2011) examined emotional and cognitive factors in groups of children with and without mathematical learning disabilities (MLD). In the present research, we focused instead on children with high or low levels of MA and investigated their profiles in different areas of cognitive and academic achievement. Given the specificity of the worrying thoughts, we hypothesized that children with HMA would show specific impairments in most of the mathematical tasks proposed, but no differences in reading and writing tasks. In addition, we expected children with high levels of math anxiety (HMA) to be more impaired in WM and inhibitory control than children with low levels of math anxiety (LMA), since task-irrelevant thoughts would disrupt the former's performance because they would reduce the pool of resources available (Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007).

METHODS

Screening Phase

The initial screening phase involved a sample of 135 children (64 Males, 71 Females) aged 11–13 years ($M = 155.22$ months; $SD = 12.78$), comprising 47 children in sixth grade, 49 in seventh, and

39 in eighth grade, all attending state schools in Northern Italy and coming from families of middle socioeconomic status.

Parental consent was obtained for all the children prior to testing. Children with intellectual disabilities, learning disabilities, or an inadequate command of the Italian language were excluded from the study. Students participating in the screening phase were tested collectively in their classrooms during regular class hours.

Children with a HMA or LMA were identified on the basis of their performance and anxiety levels recorded by means of screening tests. Their level of MA was measured with an adaptation of the Abbreviated Math Anxiety Scale (AMAS, Hopko et al., 2003), while their general level of anxiety was tested using the Revised Children's Manifest Anxiety Scale—2nd Edition (RCMAS-2, Reynolds and Richmond, 2012). To control for general cognitive skills, we tested the students' vocabulary (PMA-Verbal meaning, Thurstone and Thurstone, 1981)[1].

The inclusion criteria for LMA children were as follows: (a) average scores for MA; (b) average scores for general anxiety; and (c) average scores for PMA-Verbal meaning. The inclusion criteria for the HMA group were: (a) scores higher than 1 SD for MA; (b) average scores for general anxiety; and (c) average scores for PMA-Verbal meaning. From the initial sample, only 36 children had scores higher than 1 SD on MA. Four children were excluded: three did not have average scores on the PMA Verbal meaning, and one showed scores higher than 1 SD on general anxiety. Thus, our final group was composed of 32 HMA children.

Participants

Our final sample consisted of 34 LMA children (21 females), including 9 sixth-, 16 seventh-, and 9 eighth-graders, and 32 HMA children (22 females), with 11 of them in sixth, 12 in seventh, and 9 in eighth grade. The groups' characteristics and appropriate statistics are shown in **Table 1**.

In the second phase, the two groups of children were tested during two different sessions to assess any differences between their academic and cognitive aspects by means of: (a) a collective session during which the students completed tests on their mathematical proficiency and reading comprehension; and (b) individual sessions in which they were assessed on their word reading and writing abilities, and their working memory.

MATERIALS

Screening Phase

The Abbreviated Math Anxiety Scale (AMAS; derived by Hopko et al., 2003) is a self-report MA questionnaire adapted to middle-school students[2] . With 9 items, it is the shortest valid MA scale, but in the original version it has been shown to be as effective as the longer Maths Anxiety Rating Scale (MARS; Hopko, 2003) (e.g., internal consistency: Cronbach's $\alpha = 0.90$; 2-week test-retest reliability: $r = 0.85$; convergent validity of AMAS and MARSR $r = 0.85$). Using a 5-point Likert scale, participants indicate how much anxiety (e.g., 1 = low anxiety; 5 = high anxiety) they would feel during certain situations involving maths. In our adaptation to middle-school students two items were slightly modified (item 1: "Having to use the tables and math formulas in the back of a math book"; item 6: "Being given an assignment of many difficult math exercises due to the next class meeting"). The Cronbach's α calculated on our sample was = 0.81.

The Revised Children's Manifest Anxiety Scale: Second Edition (RCMAS-2; Reynolds and Richmond, 2012) is a self-report questionnaire used to identify the source and level of GA in children from 6 to 19 years old. It consists of 49 items with a simple yes/no response format and is divided into 5 different scales: physiological anxiety, worries, social anxiety, defensiveness and total anxiety (internal consistency: physiological anxiety Cronbach's $\alpha = 0.68$; worries $\alpha = 0.80$; social anxiety $\alpha = 0.78$; defensiveness $\alpha = 0.70$; total anxiety $\alpha = 0.89$).

Verbal Meaning, Primary Mental Abilities (PMA, Thurstone and Thurstone, 1981). The verbal meaning subtest comprises 51 trials in which participants are given a target word and are required to choose among five alternative words which one has the same meaning of the target. The final score is given by the sum of correct responses minus incorrect responses The test-retest reliability is $r = 0.92$.

Academic Achievement Measures

Mathematics Achievement

Mathematical abilities were assessed using the AC-MT 11–16 standardized mathematics test (Cornoldi and Cazzola, 2004) designed for sixth- to eighth-graders. This test assesses calculation procedures and number comprehension by means of a set of paper-and-pencil tasks that can be grouped into two areas: "written calculation" and "number knowledge." In the former, participants have to solve eight written multi-digit calculations (two additions, two subtractions, two multiplications and two divisions). The latter contains tasks demand involve number magnitude judgments, place-value (i.e., syntax) comprehension, logical reasoning, approximate calculations, and fact retrieval (i.e., solve 32 simple calculations in a time limit of 2 min). The test re-test reliability is $r = 0.83$. Z-scores were calculated on the basis of the normative sample according to grades.

Reading and Writing Achievement

Reading Comprehension

This task was derived from the standardized MT battery (Cornoldi et al., 2010). It focuses mainly on the student's ability to find appropriate information within a text to answer a set of comprehension questions, enabling comprehension to be considered separately from the contribution of decoding and memory of the text (Cornoldi and Oakhill, 1996). Participants are asked to silently read a passage and then answer some questions related to the text. They are given an unlimited amount of time

[1]Traditionally vocabulary was considered a good indicator of intelligence (Binet and Simon, 1905), and in fact vocabulary measures have very high loading on the g-factor (Carroll, 1993; Flanagan and Kaufman, 2004).

[2]The adaptation mainly regarded the type of language used. In particular, in two items the word "expression" instead of the original word "problem" was used, since children in Italian middle school level are more exposed to expression exercises.

TABLE 1 | Descriptive (M, means; SD, standard deviations) and one-way ANOVAs of the comparison between children with low (LMA) and high levels of math anxiety (HMA).

	LMA *M(SD)*	HMA *M(SD)*	$F_{(1,64)} =$	*p*	η^2
Age in months	155.62 (10.56)	156.06 (14.46)	0.02	0.881	> 0.001
GENERAL COGNITIVE AND EMOTIONAL PROFILES					
PMA—vocabulary	14.50 (7.86)	13.22 (7.47)	0.46	0.502	0.007
RCMAS -2 (T scores)	53.26 (7.11)	55.06 (9.04)	0.81	0.370	0.013
AMAS	19.56 (3.03)	29.16 (3.45)	144.91	0.001	0.690
ACADEMIC ACHIEVEMENT (Z SCORES)					
Mathematical proficiency, AC-MT battery					
Written calculation	0.04 (0.82)	−0.66 (0.93)	10.67	0.002	0.143
Magnitude judgment	0.37 (0.88)	−0.12 (1.05)	4.31	0.040	0.063
Place-value comprehension	−0.07 (0.99)	−0.50 (1.10)	2.84	0.090	0.042
Logical reasoning	−0.09 (0.93)	−0.66 (1.09)	5.17	0.030	0.075
Approximate calculation	−0.16 (0.86)	−0.36 (0.98)	0.83	0.370	0.013
Fact retrieval	0.01 (0.83)	−0.67 (0.96)	9.20	0.003	0.126
Reading comprehension					
Comprehension	−0.14 (0.71)	−0.41 (0.98)	1.67	0.210	0.025
Word reading and writing					
Reading speed	0.40 (1.29)	.71 (0.94)	1.23	0.270	0.019
Reading accuracy	0.37 (1.13)	0.61 (1.01)	0.78	0.380	0.012
Writing accuracy	0.21 (2.61)	−0.13 (0.94)	0.45	0.500	0.007
Working memory measures					
STM—Number of words	23.35 (4.22)	19.63 (4.35)	6.35	0.014	0.090
LST—Number of words	24.12 (4.28)	21.78 (4.26)	4.94	0.030	0.072
LST—Intrusion errors	1.88 (1.45)	3.47 (2.51)	10.01	0.002	0.135

AMAS, Abbreviated Math Anxiety Scale (Hopko et al., 2003); RCMAS, Revised Children's Manifest Anxiety Scale -2nd Edition (Reynolds and Richmond, 2012); STM, Short-Term Memory; LST, Listening Span Test.

to complete the task and they are allowed to consult the text as often as they wish. (Cronbach's $\alpha = 0.77$). Z-scores were calculated on the basis of the normative sample according to grades.

Word Reading and Writing

These tasks are subtests of a battery specifically for assessing developmental dyslexia and dysorthographia (Sartori et al., 2007). The battery has an adequate reliability (e.g., mean test-retest coefficients are 0.77 for speed and 0.56 for accuracy). In the Word reading task participants are asked to read four lists of isolated words aloud and as accurately and rapidly as possible. The material varies in frequency and concreteness, starting with a list of very common and concrete words, followed by lists of words of decreasing frequency and concreteness. Reading speed is calculated by dividing the number of syllables read by the time (in seconds) taken to read them. Accuracy corresponds to the number of words read incorrectly. The Word writing task involves participants writing lists of words. The materials are presented aloud by the experimenter who dictates the words at a constant rhythm (about one word every 3 s). The score is represented by the number of words that are written incorrectly. Z-scores were calculated on the basis of the normative sample according to grades.

Verbal Short-Term and Working Memory Tasks

Verbal Short-Term Memory (STM)

To assess the student's short-term memory ability, we used the Word Span Forward task (Passolunghi and Siegel, 2004), which involves the passive storage and recall of verbal information (Swanson, 1993; Cornoldi and Vecchi, 2000). The task consists in the presentation of lists of words of increasing length (from 3 to 8 words) and the participant has to remember the words in the same order as they were presented. Two trials are run for each length of word list. There is no time limit for recalling the words in the same, forward order. The raw score is the number of words correctly remembered throughout the testing session.

Listening Span Task (LST)

To analyze working memory we used an adaptation of the listening span test devised by Daneman and Carpenter (1980). This test engages the participant in a dual task: the child has to judge whether a sentence is true or false and also retain the last word in the sentence. The sentences are arranged into sets of different length, from 2 to 5 sentences per set, with two sentences in the first sets and increasing the number of sentences in later sets. At the end of each set of sentences, immediately after saying whether a sentence was true or false, participants are asked to recall the last word in each sentence (in the same order as they were presented) and to be careful to avoid naming non-final words. Two scores are obtained from this recall task: one for the raw number of words recalled correctly, and one for the number of non-target words erroneously recalled (intrusion errors). The latter score is considered a measure of cognitive inhibition processes (De Beni et al., 1998; Passolunghi and Siegel, 2001, 2004).

Procedure

The experimental procedure described here was in accordance with the Declaration of Helsinki (Sixth revision, 2008). After assigning them to one or other group the children were tested during two different sessions lasting approximately 30 min each. They were first tested collectively with the AC-MT 11–14 standardized arithmetic battery (Cornoldi and Cazzola, 2004) and the reading comprehension task (MT battery, Cornoldi et al., 2010). Then in a second session, the children were tested individually in a quiet room away from their classroom, where the word reading and writing subtests (Sartori et al., 2007) and the STM and WM tasks were administered.

RESULTS

First, we compared LMA and HMA groups in the screening measures, academic and WM tasks to identify any statistically significant differences. **Table 1** summarizes the performance of the LMA and HMA children in all the tests administered. All statistical analyses (see **Table 1**) refer to the comparison of the two groups using one-way ANOVA; the effect sizes (η_p^2) are also reported.

Screening Phase

LMA and HMA groups did not differ in terms of PMA-Vocabulary or generalized anxiety ($p > 0.37$); however, the HMA group showed much higher levels of MA than the LMA group $F_{(1,64)} = 144.91$; $p < 0.0001$. In addition, the two groups were matched for age $F_{(1,64)} < 1$, and gender χ^2 $(1, N = 66) = 0.35$; $p < 0.55$.

Academic Achievement Tasks

For mathematical proficiency, as expected, we found significant differences in the written calculation task, and in some tests in the "number knowledge" part of the AC-MT battery. In particular, the two groups showed significant differences in four tests—Written calculation, Magnitude judgment, Logical reasoning and Fact retrieval—for all of which the LMA group outperformed the HMA group by more than 0.5 standard deviation.

When the groups were compared on the other academic measures, we found no significant differences for reading comprehension accuracy or the word reading and writing measures (see **Table 1**). The mean z-scores for reading comprehension and word reading indicate that LMA children performed slightly better than HMA children. The opposite pattern (falling short, here again, of statistical significance) emerged for the writing tasks: children with HMA were slightly more accurate in word writing than those with LMA.

TABLE 2 | Percentage of individuals correctly identified by the model.

Observed	Predicted		
	Group		Percentage identified correctly
	LMA	HMA	
LMA	27	7	79.4
HMA	10	22	68.8
Overall			74.2

LMA, low mathematical anxiety; HMA, high mathematical anxiety.

Working Memory Tasks

As shown in **Table 1**, significant differences were found between the two groups in all the measures of verbal short-term and working memory. Individuals with HMA recalled significantly fewer words than LMA children in the STM and LST and made more intrusion errors in the LST.

Logistic Regression

To see which tasks could discriminate between individuals with HMA and those with LMA, we conducted a likelihood-ratio logistic regression analysis using the Wald method. Logistic regression applies maximum likelihood estimation after transforming the dependent into a logit variable (the natural log of the odds of the dependent variable occurring or not).

The model created included one dependent—or criterion—variable of the LMA or HMA groups and two independent—or predictor—variables found significant (i.e., fact retrieval, *Wald* $\chi^2(1) = 7.16$, $p = 0.007$, and intrusion errors in the LST, *Wald* $\chi^2(1) = 7.00$, $p = 0.008$, see **Table 2**), $R^2{}_{(Cox\&Snell)} = 0.24$.

As shown in **Table 2**, the two predictor variables were able to identify 79.4% of the LMA children and 68.8% of the HMA children. In other words, the probability that a child of the LMA was correctly identified using the predictor variables is 79.4%; whereas the probability that a child of the HMA group was correctly identified using the predictor variables is 68.8%. A Hosmer-Lemeshow test was conducted to examine the goodness of fit of our logistic model against actual outcomes. The Hosmer-Lemeshow test yielded a $\chi^2(7) = 2.72$, $p = 0.91$, indicating a good fit.

DISCUSSION

The main aim of this study was to analyze the academic achievement and cognitive profiles of children with HMA and LMA in middle school students, given that most previous studies were conducted on young adults, or children in the early stage of math learning. For this reason, we selected children in sixth to eighth grade who had HMA but not generalized anxiety, and a group with LMA matched for age, gender, generalized anxiety, and vocabulary. The children were tested on reading decoding, reading comprehension, mathematics achievement, and also on verbal short-term and working memory. We thus analyzed whether children with HMA were only weak in mathematics, but not in reading and writing, and whether these children with HMA had a lower WM performance (and associated difficulty with inhibiting irrelevant information) than children with LMA.

Concerning their academic achievement, children with HMA performed less well than those with LMA in all mathematical tasks except for the approximate calculation subtest, whereas the two groups did not differ on reading decoding, reading comprehension and word dictation. In agreement with previous findings (Hembree, 1990; Ashcraft and Krause, 2007), the present study thus confirmed that high levels of mathematics anxiety coincide with a high likelihood of a poor academic performance, but only in mathematics. It is worth noting that the negative relationship between math anxiety and achievement does not produce a general impairment in all achievement tasks, in fact, only on mathematics achievement children with HMA were specifically impaired (see also Ashcraft and Moore, 2009).

As for the cognitive profile of children with high and low levels of MA, our results showed that children with HMA performed less well on both verbal STM and WM tasks. Unlike several previous studies, we found our HMA children impaired in a verbal STM task involved no digits or computations (Ashcraft and Kirk, 2001; Mammarella et al., 2015). Such an impairment on verbal WM tasks had already been reported (Ashcraft and Kirk, 2001; Eysenck et al., 2007; Ramirez et al., 2013; Mammarella et al., 2015), and suggests that anxiety may reduce verbal WM resources. In particular, Ramirez et al. (2013) who studied children attending first and second grades revealed that children with high WM showed a pronounced negative relation between math anxiety and math achievement, hence the present study—using a different approach—extend the negative relation among MA, WM, and math achievement to older students. In another recent, study testing middle school students with high and low MA, Mammarella et al. (2015) showed that students with HMA with and without math difficulties performed worse than students with typical development in a verbal WM task (i.e., backward words span task), in agreement with the present findings. However, the backward words span task does not allow to analyze the ability to inhibit irrelevant information in WM (Passolunghi and Siegel, 2001) and that is why we chose a typical dual-span task to investigate WM processes in the present study. Our children with HMA, in fact, made more intrusion errors, thus showing to be unable to inhibit irrelevant information in WM, than the children with LMA.

It is worth noting that our HMA group revealed not only weaknesses in inhibiting irrelevant information in WM, but also specifically failed in mathematical tasks and not in verbal (reading and writing) tasks. This pattern of results is consistent with the ACT model proposed by Eysenck and Calvo (1992), confirming that math anxiety interferes with the efficient functioning of the goal-directed attentional system, reducing attentional control specifically on math-related tasks. This conclusion is strengthened by the results of our logistic regression, in which only intrusion errors in the LST and fact retrieval emerged as significant predictors of math anxiety: these two measures correctly identified around 79% of children with LMA and 69% of children with HMA. It is worth noting that our fact retrieval task involved producing the correct answer for simple calculations under time constraints, and children with HMA may be at a greater disadvantage when under pressure to respond promptly. Faust et al. reported (1996) finding no differences relating to math anxiety in their sample's accuracy on untimed paper-and-pencil tests, but the same stimuli generated anxiety effects in the task with time constraints.

A possible limitation of our study lies in our choice of STM and WM tasks. In fact, only the verbal component was investigated, so further studies should compare children with HMA and LMA on both verbal and visuospatial STM and WM tasks. Gender-related differences were not examined in the present study either. When Devine et al. (2012) studied a large sample of children of middle school, they found that girls and boys performed equally well in math, but girls experienced more math anxiety than boys. In our sample too, around 70% of the participants with HMA were girls. Further studies should nonetheless analyze gender-related differences in mathematics anxiety, WM and academic achievement in more depth. In addition, the present study was not able to disentangle the direction of the relationship among MA, WM and mathematics performances, therefore, further research should analyze whether WM (and in particular difficulties in inhibiting irrelevant information) mediates the effects on mathematics performances and the relationship between MA and arithmetic achievement. Finally, ours was a cross-sectional study, whereas a longitudinal study would be able to generate information on how the relationship between mathematics anxiety, WM and math performance evolve over time.

The present study has some implications for educators. First, weak math abilities and low WM capacity may be seen as risk factors for math anxiety. Math anxiety seems to have a straightforward influence on cognitive processing, not only impairing WM, but also making children with HMA perform less well than children with LMA in mathematical tasks. Being aware of which middle school students experience high levels of MA could help teachers try to avoid the vicious circle triggered when anxiety leads to the avoidance of situations involving math tasks. For example, given that pressure may affect math performances of students with HMA, teachers should avoid time constraints for students showing high levels of MA; in addition, teachers should provide students with feedback about the correctness of their responses, since previous findings showed that worries tent to increase after negative feedback, and decrease after positive feedback (Daniels and Larson, 2001).

In conclusion, the present study showed that middle school students with HMA are at greater risk than those with LMA of performing poorly in mathematics achievement measures. HMA students also performed less well in verbal STM and WM tasks, and were less able to inhibit irrelevant information. Finally, measures of inhibitory control and fact retrieval emerged as the best predictors for identifying children with high or low levels of MA.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

The study was partially supported by grant Fra2014 to the first author.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

MINI REVIEW
published: 07 January 2016
doi: 10.3389/fpsyg.2015.01987

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The Chicken or the Egg? The Direction of the Relationship Between Mathematics Anxiety and Mathematics Performance

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This review considers the two possible causal directions between mathematics anxiety (MA) and poor mathematics performance. Either poor maths performance may elicit MA (referred to as the Deficit Theory), or MA may reduce future maths performance (referred to as the Debilitating Anxiety Model). The evidence is in conflict: the Deficit Theory is supported by longitudinal studies and studies of children with mathematical learning disabilities, but the Debilitating Anxiety Model is supported by research which manipulates anxiety levels and observes a change in mathematics performance. It is suggested that this mixture of evidence might indicate a bidirectional relationship between MA and mathematics performance (the Reciprocal Theory), in which MA and mathematics performance can influence one another in a vicious cycle.

Keywords: mathematics anxiety, mathematics performance, debilitating anxiety, deficit theory, cognitive interference, working memory, educational psychology

OPEN ACCESS

Edited by:
Tifei Yuan,
Nanjing Normal University, China

Reviewed by:
Belinda Pletzer,
University of Salzburg, Austria
Brenda R. J. Jansen,
University of Amsterdam, Netherlands

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Specialty section:
This article was submitted to Cognition,
a section of the journal Frontiers in Psychology

Received: *25 July 2015*
Accepted: *12 December 2015*
Published: *07 January 2016*

Citation:
Carey E, Hill F, Devine A and Szücs D (2016) The Chicken or the Egg? The Direction of the Relationship Between Mathematics Anxiety and Mathematics Performance. Front. Psychol. 6:1987. doi: 10.3389/fpsyg.2015.01987

INTRODUCTION

A pertinent question in mathematics anxiety (MA) research is whether MA causes poor maths performance, or whether poor maths performance elicits MA. This paper will review the extant literature to consider the possible models, and to provide greater insight into the nature of the MA-maths performance relationship.

Mathematics anxiety can be defined as a state of discomfort around the performance of mathematical tasks (Ma and Xu, 2004), and is generally measured using self-report trait anxiety questionnaires. There is broad consensus that MA is linked to poorer maths performance, with studies typically observing small to moderate negative correlations (Ashcraft and Krause, 2007; Devine et al., 2012; Zakaria et al., 2012; Jansen et al., 2013). For example, two meta-analyses found correlations of −0.27 and −0.34 between MA and maths performance (Hembree, 1990; Ma, 1999). Similar correlations have long been observed in non-maths specific anxiety, for example, between test anxiety and performance (Mandler and Sarason, 1952).

However, studies attempting to elucidate the direction of the MA-maths performance link are in conflict (Devine et al., 2012) and there is a paucity of longitudinal studies on the subject. Furthermore, the question is not trivial, since it should feed directly into educational policy. Beilock and Willingham (2014, p. 29) note that some believe "math(s) anxiety is just another name for 'bad at math(s);"' if policy-makers share this belief, to reduce students' MA, effort and money will be targeted at courses to improve their maths. If the relationship is in fact in the other direction, such efforts are likely to be ineffective and it would be better to focus on alleviating MA to improve maths performance (Beilock and Willingham, 2014). On the other hand, if poor performance causes MA, it is possible that alternative teaching methods could mitigate this.

Knowing the direction of the MA-maths performance relationship has further implications for education and psychology research. For example, if poor performance is seen to increase MA, computer-adaptive programs may offer a way to ensure that students do not experience excessive failure in their maths learning, by adjusting the difficulty level to an individual student's ability (as in Jansen et al., 2013). On the other hand, if MA reduces maths performance, further research is required into remediation of MA, particularly methods which may be undertaken in the maths classroom. For example, writing about emotions prior to a maths test has been seen to increase performance in those with high MA (Park et al., 2014).

The anxiety-performance link has two possible causal directions, which have been extended into the specific field of MA (Hembree, 1990). The first of these directions is encapsulated by the Deficit Theory, which claims that poor performance, for example in tests or maths, leads to higher anxiety about that situation in the future (Tobias, 1986). Proponents of the Deficit Theory believe that prior maths performance deficits lead to memories of poor maths performance, generating MA (Hembree, 1990).

The second causal direction is that anxiety reduces performance by affecting the pre-processing, processing, and retrieval of information (Wine, 1971; Tobias and Deutsch, 1980; Tobias, 1986), henceforth referred to as the Debilitating Anxiety Model. Prior to information processing, MA may influence learning by disposing individuals to avoid maths-related situations (Hembree, 1990; Chinn, 2009). Later, at the stages of processing and recall, MA may influence performance by cognitive interference. For example, MA may tax working memory resources, which are vital for the processing and retrieval of mathematical facts and methods (Ashcraft and Kirk, 2001; Ashcraft and Krause, 2007; Krinzinger et al., 2009). Indeed, research indicates that positive emotions enhance learning by increasing the persistence, strategy and recruitment of cognitive resources (Pekrun et al., 2002; Sabourin and Lester, 2014; Verkijika and De Wet, 2015) and that negative emotions, including anxiety, do the opposite (Meyer and Turner, 2006; Sabourin and Lester, 2014; Verkijika and De Wet, 2015). The multitude of studies indicating that emotions have an effect on general achievement supports the application of this theory to MA more specifically.

It is important to note that regardless of causal direction, other factors may well mediate or moderate the relationship between anxiety and performance. For example, academic self-concept has been identified as a factor related to academic performance (as in Guay et al., 2003), and low maths self-concept is related to MA (Ahmed et al., 2012). This mini-review focuses only on the direction of the relationship between MA and performance, rather than its many possible mediators and moderators.

Additionally, since deficit and debilitating anxiety theories may be applied to anxiety outside of the field of maths, we sometimes examine research into anxiety more generally. Whilst this forms a theoretical basis for deficit- and debilitating anxiety-based models, it is possible that MA and maths performance have a different causal relationship than do other forms of anxiety. Researchers have identified certain key beliefs held about maths (see Theoretical Review in Jackson, 2008 for a summary), which could moderate causal relationships, making MA different in nature from other forms of anxiety. Thus we focus on research on MA specifically, using research into other anxiety types only where similar research on MA is unavailable but may be useful to carry out.

THE DEFICIT THEORY

Evidence revealing that children with mathematical learning disabilities are often found to have disproportionately high levels of MA, provides support for the Deficit Theory. It is likely that, in at least some cases, having especially poor maths performance in early childhood could elicit MA. In Italian fourth graders and Canadian 7–13 year-olds, those with mathematical learning disabilities display higher levels of MA than typically developing children (Rubinsten and Tannock, 2010; Passolunghi, 2011). However, whilst these studies of developmental dyscalculia and mathematical learning disabilities indicate that specific cases of MA are related to poor performance, with only 1–6% of the population suffering from developmental dyscalculia (Devine et al., 2013), such findings cannot straightforwardly be generalized to the typically developing child. It should also be noted that cognitive resources are not the only possible deficit which could cause poor maths performance and MA. For example, self-regulation deficits have been associated both with MA (Jain and Dowson, 2009; Kramarski et al., 2010) and decreased maths performance (Lee et al., 2014).

Longitudinal studies of typically developing children and adolescents also provide support for the Deficit Theory. One of few longitudinal studies in this area looked at adolescents in the United States, and found significant correlations (−0.11 to −0.2) between a student's academic performance in one year and their MA in the following year (Ma and Xu, 2004). These correlations were stronger than those found between a student's MA in one year and their academic performance in the following year, indicating that maths performance may cause MA, thus providing support for the Deficit Theory. Nevertheless, these results should be taken with caution. The mechanisms of influence proposed by the Debilitating Anxiety Model, particularly cognitive interference, may be more immediate than from one academic year to the next, since the effect of anxiety on recall would cause a fairly immediate performance decrement in those with high MA. If the Debilitating Anxiety Model were in operation, the effect of MA on performance may not be visible in MA-performance correlations from one year to the next. Thus whilst this research supports the idea that low maths performance may cause anxiety, it says nothing about whether there is also a relationship in the other direction.

In further support of the Deficit Theory, additional longitudinal research into MA in early adolescence similarly found that one year's perceived maths ability was moderately correlated with the following year's MA (Meece et al., 1990). However, MA was only measured in the second year of the 2-year study, and again MA and the same year's performance were not compared, making comparison between the Deficit and Debilitating Anxiety models unfeasible.

Some researchers have suggested that MA in adults may result from a deficit in basic numerical processing, which would be more in line with the Deficit Theory. For instance, Maloney et al. (2010, 2011) have revealed that adults with high MA have numerical processing deficits compared to adults with low MA. The authors tentatively stated that the findings from these studies indicate that "MA may result from a basic low-level deficit in numerical processing that compromises the development of higher level mathematical skills" (Maloney et al., 2011, p. 14). However, as these studies did not follow the developmental trajectory of MA or the acquisition of mathematics skills in their participants, the authors could not determine the direction of the MA-maths performance relationship. Importantly, these results do not preclude the possibility that highly maths anxious adults' basic numerical abilities were impaired because they have avoided mathematical tasks throughout their education and in adulthood due to their high levels of MA, which would be more consistent with the Debilitating Anxiety Model.

Genetic studies may help to elucidate whether maths performance deficits do in fact emerge first and cause MA to develop. One such study suggests that 9% of total variance in MA stems from genes related to general anxiety, and 12% from genes related to maths cognition (Wang et al., 2014). This may indicate that for some, MA is caused by a genetic predisposition to deficits in maths cognition. However, it does not preclude the possibility that the relationship between MA and performance is reciprocal. It may be useful to study those individuals who experience MA but do *not* have the genes associated with maths performance deficits, in order to see whether performance deficits can emerge from MA alone.

THE DEBILITATING ANXIETY MODEL

Many alternative studies across childhood, adolescence, and adulthood provide support for the Debilitating Anxiety Model, suggesting that MA can impact performance at the stages of pre-processing, processing and retrieval of maths knowledge. Hembree's (1990) meta-analysis included evidence suggesting that adolescents with MA may avoid maths-related situations, pointing to the idea that MA is likely to exert an influence on performance by reducing learning opportunities. Similarly, Ashcraft and Faust (1994) found that adults with high MA answered maths questions less accurately but more quickly than those with lower levels, and Morsanyi et al. (2014) found that MA was associated with decreased cognitive reflection during mathematics word problems. Such data suggest that adults with MA may avoid processing mathematical problems altogether which could lead both to reduced maths learning and to lower maths performance due to rushing. Further support comes from the wealth of evidence indicating that adults with MA are less likely to enroll on college or university courses involving mathematics (for a review see Hembree, 1990). Even in young children, task-avoidant behaviors have been found to reduce maths performance (Hirvonen et al., 2012). Furthermore, recent research suggests that anticipation of maths causes activation of the neural 'pain network' in high MA individuals, which may help to explain why high MA individuals are inclined to avoid maths (Lyons and Beilock, 2012b). This strongly suggests that MA is likely to influence adults' maths outcomes at the pre-processing level, providing support for the Debilitating Anxiety Model.

Additionally, there is evidence that MA impairs maths performance during maths processing by taxing processing resources. Eysenck and Calvo's (1992) Processing Efficiency Theory suggests that worry reduces working memory's processing and storage capacity, thus reducing performance. Ashcraft and Kirk (2001) found a negative correlation between college students' MA levels and their working memory span. Further, Ashcraft and Krause (2007) found an interaction between adults' MA and their performance on high and low working-memory load maths problems, with high working-memory load questions being more affected by MA. Thus, MA appears to exert an effect on performance by compromising the working-memory functions of those with high MA. It is also possible that MA affects strategy selection, leading individuals to choose simpler and less effective problem-solving strategies and thus impairing their performance on questions with a high working-memory load (Beilock and Decaro, 2007). This is supported by evidence suggesting that those with high working-memory, who usually use working-memory intensive strategies, are more impaired under pressure than those who tend to use simpler strategies (Beilock and Carr, 2005; Ramirez et al., 2013).

Experimental studies attempt to solve the problem of the causal ordering of MA and maths deficits by manipulating MA only and observing whether this has an impact on performance. For example, it has been observed that engaging in free-writing about emotions prior to a maths test, in order to alleviate MA-related intrusive thoughts, increases performance (Park and Ramirez, 2014). Furthermore, MA is observed to be less linked to maths performance when maths tests are not timed, indicating that anxiety resulting from time-pressure reduces test performance (Faust et al., 1996). Both of these studies provide support for the cognitive interference proposed within the Debilitating Anxiety Model, since they highlight the negative effects MA can have on maths test performance.

Stereotype threat studies manipulate anxiety levels in the opposite direction, and also indicate that the Debilitating Anxiety Model may best explain the causal ordering of the MA and maths performance relationship. Stereotype threat is the situation in which members of a group are, or feel themselves to be, at risk of confirming a negative stereotype about their group. Under stereotype threat, individuals are seen to perform more poorly in a task than they do when not under this threat. It is posited that this is due to anxiety elicited by the potential to confirm or disconfirm a negative stereotype about one's group (Steele and Aronson, 1995; Schmader et al., 2008).

Whilst not all studies of children and adolescents demonstrate the effect of stereotype threat on maths performance (see Ganley et al., 2013 for discussion), it appears that at least under some conditions, certain populations show an effect from stereotype threat based anxiety manipulations. For example, Galdi et al. (2013) found that Italian 6–7 year-old girls showed a performance decrement after completing a task to elicit stereotype threat prior to their maths assessment. The effect of increasing anxiety by stereotype threat can be seen in adults as well as children. For example, it has been observed that presenting women with a female role model who doubted her maths ability reduced their performance in maths problems compared with a control group who were presented with a non-doubtful female role model (Marx et al., 2013). This finding has been supported by other studies in adults (Spencer et al., 1999; Schmader, 2002; Gerstenberg et al., 2012; Seitchik et al., 2012). Deficits seen in women under maths stereotype threat appear to be mediated by a working-memory impairment, supporting the idea that MA influences performance by taxing working-memory resources (Beilock et al., 2007). Further, stereotype threat based maths performance decrements have been observed based on race and income level as well as gender (Tine and Gotlieb, 2013). Such data is in accordance with the Debilitating Anxiety Model, since anxiety manipulations demonstrate the deleterious effects of MA.

Neuroimaging data also suggest that the Debilitating Anxiety Model is in operation. Lyons and Beilock (2012a) carried out an fMRI study on high and low MA adults. Whilst there was a significant performance difference between high and low MA individuals, within-group correlations between MA and performance were not observed. This raises the question of how some individuals with very high MA outperform those with slightly lower, but still relatively high, MA. Neuroimaging revealed that in high MA individuals, increased activity in frontoparietal regions (involved in the cognitive control and reappraisal of negative emotions) prior to performing maths tasks was correlated with higher performance. This indicates that some high MA individuals are able to use higher cognitive functions to mitigate the effect of MA on performance, and may reveal why correlations between MA and performance tend to be relatively low, albeit significant. This is highly supportive of the Debilitating Anxiety Model: it appears that individuals who are better able to suppress their negative emotional response to maths have less of a performance deficit, and therefore suggests that the original performance deficit was caused by negative and intrusive thoughts (Lyons and Beilock, 2012a). A more recent fMRI study reached a similar conclusion after finding that MA did not affect activation in brain areas known to be involved in numerical processing (Pletzer et al., 2015). MA was instead linked with reduced deactivation of the Default Mode Network (see Pletzer et al., 2015 for details), indicating a preoccupation with the emotional value of numerical stimuli. This suggests that performance deficits in high MA individuals are more related to emotional interference than cognitive deficits.

THE RECIPROCAL THEORY

The evidence is conflicting; some studies provide data which appears to fit the Deficit Theory, whereas others provide more support for the Debilitating Anxiety Model. However, there may be an explanation for such conflicting evidence. It may in fact be indicative of the very nature of the MA-maths performance relationship; whilst poor performance may trigger MA in certain individuals, it may further reduce their maths performance in a vicious cycle (as endorsed in Jansen et al., 2013). Ashcraft et al. (2007) propose a model in which MA can develop either from non-performance factors, such as biological predisposition, or from performance deficits. They argue MA may then cause further performance deficits, via avoidance and working-memory disruption, supporting the Reciprocal Theory. The question of whether the MA-maths performance relationship is in fact reciprocal is likely to be best answered by longitudinal studies across childhood and adolescence, since only longitudinal data can determine whether MA or weak performance is first to develop.

However, there is limited non-longitudinal data which already suggests that the Reciprocal Theory may provide the best explanation for the MA-maths performance relationship. For example, data collected in Singapore suggest that previous achievement may affect a student's MA levels and that MA in turn affects future performance (Luo et al., 2014). Pekrun (2006) provides a putative reciprocal model in which control and value appraisals predict academic anxiety, which affects performance, and further proposes indirect feedback loops from performance to appraisals and emotions. In light of the conflicting evidence discussed, such complex models involving feedback loops between multiple factors, including MA and maths performance, are likely to provide the best explanation of the relationship between MA and maths performance.

Whilst researchers often provide data supporting either the Deficit Theory or the Debilitating Anxiety Model rather than endorsing a reciprocal model, it is possible that this relates to methodological constraints. In particular, the mechanisms proposed by the Deficit Theory are long-term, with the detrimental effect of poor performance on anxiety levels occurring over a number of years. This may be why the Deficit Theory is often supported by long-term longitudinal studies (e.g., Ma and Xu, 2004). On the other hand, the Debilitating Anxiety Model, particularly cognitive interference, proposes some immediate mechanisms for anxiety's interference with performance (e.g., taxing working memory resources, as discussed in Ashcraft and Krause, 2007). This could explain why the Debilitating Anxiety Model is best supported by experimental studies such as those into stereotype threat. It is quite plausible that the limitations of carrying out just one study type (such as a long-term longitudinal investigation or a short-term experimental study) mean that studies reveal only one of two operational causal directions. Examining a variety of data, collected using different methods and over varied time scales, is likely to reveal whether methodological factors explain why the literature rarely supports the Reciprocal Theory.

To sum, the evidence relating to the relationship between MA and maths performance is mixed. There is research to support the Deficit Theory's claim that poor past performance can cause MA, with the strongest evidence coming from longitudinal studies (Meece et al., 1990; Ma and Xu, 2004) and studies of mathematical learning disabilities (Rubinsten and Tannock, 2010; Passolunghi, 2011). Nevertheless, in support of the Debilitating Anxiety Model, there is evidence to suggest that anxiety can have a deleterious effect on maths performance. This is strongly supported by studies across all ages which manipulate anxiety to reveal either a decrement or improvement in performance. This effect of MA on performance is likely to be mediated by working-memory impairments caused by intrusive thoughts. However, neither theory can fully explain the relationship observed between MA and maths performance. The mixture of evidence may suggest a bidirectional relationship between MA and maths performance, in which poor performance can trigger MA in some individuals and MA can further reduce performance, in a vicious cycle. Nevertheless, more longitudinal and mixed-methods research is required to provide greater understanding into this relationship and more direct support for the Reciprocal Theory.

FUNDING

This project has been funded by the Nuffield Foundation, although the views expressed are those of the authors and not necessarily those of the Foundation. The project also received funding from the James S. McDonnel Foundation.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 04 August 2015
doi: 10.3389/fpsyg.2015.01116

Statistics anxiety and performance: blessings in disguise

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Keywords: statistics anxiety, performance, state anxiety, expectancy-value theory, effort

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *30 May 2015*
Accepted: *20 July 2015*
Published: *04 August 2015*

Citation:
Macher D, Papousek I, Ruggeri K and Paechter M (2015) Statistics anxiety and performance: blessings in disguise. Front. Psychol. 6:1116. doi: 10.3389/fpsyg.2015.01116

Introduction

Statistics anxiety describes the apprehension that occurs when an individual is exposed to statistics content or problems and instructional situations, or evaluative contexts that deal with statistics. As statistics-anxious individuals always experience anxiety when doing statistics, statistics anxiety describes an enduring, habitual type of anxiety (Onwuegbuzie and Wilson, 2003; Macher et al., 2011).

A large proportion of students identify statistics courses as the most anxiety-inducing courses in their curriculum (Zeidner, 1991). Especially in subjects such as psychology, education, or sociology, statistics anxiety is widely spread among students (Onwuegbuzie and Wilson, 2003; Onwuegbuzie, 2004; Ruggeri et al., 2008). These subjects are often chosen by students with less interest and more critical self-assessments in mathematics and science. Additionally, students often underestimate the extent of statistics in these subjects (Ruggeri et al., 2008). As a consequence, statistics anxiety is supposed to lead to manifold problems over the course of students' statistics education. Students who experience higher levels of statistics anxiety are assumed to be more likely to procrastinate learning, e.g., to postpone writing term papers, to study for examinations, or to keep up with the weekly readings (Onwuegbuzie, 2004). Also, statistics anxiety is assumed to be related to less time spent on learning and to less efficient learning and study strategies (Macher et al., 2011, 2013). In the examination itself, statistics anxiety is related to worry and rumination and consumes processing capacity that would be needed for task performance (Papousek et al., 2012; Macher et al., 2013).

Consequently, statistics anxiety often is regarded to be one of the most powerful negative factors of influence on performance in statistics courses (Onwuegbuzie and Wilson, 2003). However, is this really so clear-cut? The studies in which statistics anxiety as well as performance in the examination was measured show ambiguous results concerning the relationship between statistics anxiety and performance; correlations were at best moderate, more often weak and even zero-correlations were found. Therefore, one may critically ask whether statistics anxiety really influences performance in statistics courses, and what implications this has for attaining statistical literacy. The present article takes up this question, scoping evidence from studies where statistics anxiety and performance were measured, then looking at the contribution of various indicators of performance, concluding with arguments on relevant mechanisms and implications.

Relationship between Statistics Anxiety and Performance

Evidence relating statistics anxiety with performance should be analyzed carefully because often the concept of statistics anxiety is defined and measured very imprecisely. Various studies and measurement instruments subsume variables such as academic self-concept or attitudes toward statistics under the term "statistics anxiety" (Elmore et al., 1993; Zanakis and Valenzi, 1997; Onwuegbuzie, 2004; Hanna et al., 2008). These variables, however, are not to be equated with statistics anxiety as an emotion characterized by feelings of tension, worried thoughts, mental disorganization, physiological arousal etc. in statistical contexts such as taking a test or dealing with statistical content (Papousek et al., 2012).

This scoping identified 11 studies that investigated the correlation between examination performance and statistics anxiety using an appropriate definition for anxiety. Five studies found non-significant correlations with values ranging from 0 to $r = -0.20$: Birenbaum and Eylath (1994) with first- and second-year students in education; Chiesi and Primi (2010) with measures of statistics anxiety and mid-course and final grades in a sample of psychology students; Lacasse and Chiocchio (2005) with students in a psychometrics class; Macher et al. (2013) with second-term psychology students; and Nasser (2004) with students in education. Macher et al. (2011) found a significant correlation of $r = -0.21$ in a sample of first-term students; Fitzgerald et al. (1996) report similar values. An exception to these results is the study by Lalonde and Gardner (1993), who found bivariate correlations of up to $r = -0.49$, but such findings have not been replicated since.

Three studies argued that the relationship between performance and statistics anxiety depended on students' academic background or the instructional context. Bell (2003) found zero-correlations for business students who started their university education immediately after leaving school and moderate, yet significant correlations for students who started their university education at an older age and after some vocational experiences. Bell (2001) also found significant correlations (up to $r = -0.35$) in courses which lasted a whole term in contrast to shorter courses (e.g., summer schools). Keeley et al. (2008) found significant relationships when the exam was more complex and challenging, thus difficulty is a potential moderator of the relationship. However, the highest correlation between anxiety and performance did not exceed $r = -0.40$.

Statistics Anxiety in Comparison to Other Predictors of Performance

Altogether, these low to modest correlations cast some doubt on the influence of statistics anxiety on performance. Thus, the question arises: are there better predictors for performance than statistics anxiety?

Few of the 11 studies described above have measured statistics anxiety and performance together with other predictors for performance. This is made complicated by the lack of uniform testing for acquiring statistical skills and arguments that new thinking is necessary in statistical assessment more generally (Ruggeri et al., 2011).

Some studies focused on cognitive variables. For example, inductive reasoning and high school mathematics grade were significantly related to statistics achievement in Birenbaum and Eylath (1994), basic mathematical abilities in Chiesi and Primi (2010). Mathematical ability and the level and number of courses in mathematics in school were related to performance in Lalonde and Gardner (1993) (but less than statistics anxiety). Other studies investigated the academic self-concept and/or interest in statistics. Academic self-concept is related to the actual competence in a field (Marsh and Yeung, 1997) and to more efficient learning strategies. Similarly, greater interest is linked to more time spent on tasks in a domain as well as to higher performance. In studies by Keeley et al. (2008), Macher et al. (2011, 2013), and Nasser (2004), academic self-concept and performance were significantly related. Macher et al. (2011, 2013) also connected these to interest and performance. In these two studies, self-concept and interest correlated with values between $r = 0.21$ and $r = 0.34$ with performance in the examination and showed stronger correlations with performance than statistics anxiety (Macher et al., 2011, 2013).

Generally, prior knowledge and variables that are related to prior knowledge but also self-concept and interest are strong predictors for future achievement (Marsh and Yeung, 1997). Studies which investigated the combined relationship between these variables, statistics anxiety, and performance show negative relations to anxiety but positive ones to performance (Lalonde and Gardner, 1993; Chiesi and Primi, 2010; Macher et al., 2011, 2013). These studies suggest to look not only at correlations but to investigate the interrelations between several variables.

Mechanisms Linking Statistics Anxiety to Performance

The cognitive-interference approach (Eysenck et al., 1987) proposes a direct link between anxiety and performance in an examination: Anxiety leads to increased attentiveness to task-irrelevant aspects and thus subtracts cognitive resources from the examination task at hand. The deficit approach proposes an indirect link (Musch and Bröder, 1999): lower academic achievements are attributed to adverse learning behaviors prior to an examination. Students with high statistics anxiety may invest less effort and time for learning, use less efficient learning strategies, and consequently may be ill-prepared for examinations. Yet, both approaches cannot explain zero-correlations between statistics anxiety and performance.

Findings of Macher et al. (2013) may explain these zero-correlations: Prior to the examination, statistics anxiety as well as other predictors for performance were measured (self-concept in mathematics, interest in statistics, etc.). Additionally, students rated their state anxiety twice during the examination: immediately before and in the middle of the examination. As expected, self-concept in mathematics and interest were related negatively to statistics anxiety and positively to performance. Results of the structural equation model pointed to a suppression effect between statistics anxiety and performance. The bivariate correlation between statistics anxiety and performance was around zero. Then two indirect effects with opposite signs for the correlations between statistics anxiety and two mediator variables could be observed: via state anxiety experienced immediately before and during the examination, statistics anxiety had a small but significant negative influence on performance. Statistics anxiety seemed to initiate a high level of state anxiety at the beginning of the examination which then was (at least to a

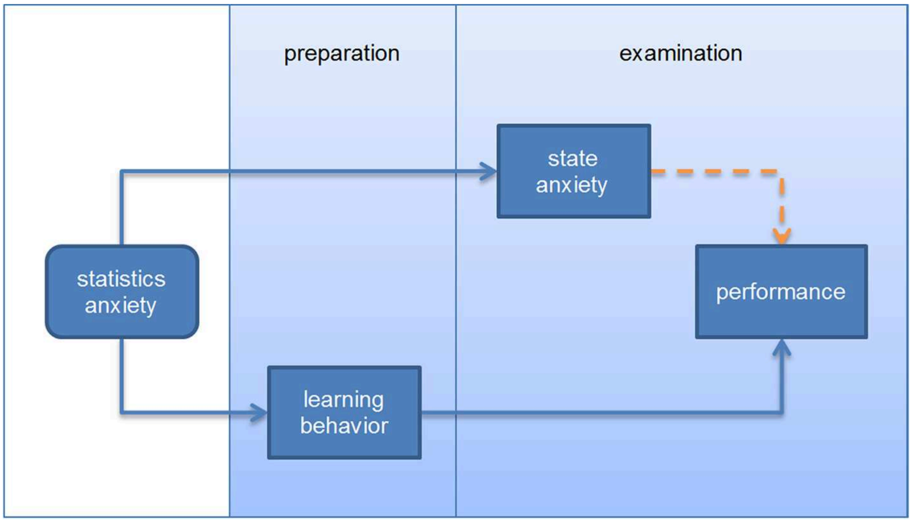

FIGURE 1 | The two-fold effect of statistics anxiety on performance.

larger degree) responsible for the maintenance of a high anxiety level throughout the examination. But statistics anxiety also had a small but significant positive influence on performance (probably through more efficient learning behaviors and/or more time spent on learning) (see **Figure 1**). Macher et al. (2013) also considered the possibility of a curvilinear relationship between statistics anxiety and performance but found no empirical evidence for this assumption. Students with extreme levels of statistics anxiety probably do not consider to study a subject with larger amounts of statistics or already fail the university entrance exams or drop out. Thus, a linear relationship should describe a student sample better.

The two-fold effect of anxiety may be explained by students' motivational goals in an educational setting: according to expectancy-value theory (Pekrun, 1988), test anxiety—and presumably statistics anxiety as well—usually reduces the motivation to approach an evaluative or a learning context because learners expect negative feelings and failure. In that instance, anxiety impairs performance by avoidance behavior such as reduced effort and less time spent for learning or avoiding the examination at all.

Depending on the situational context, such failure-avoidance motivation may have different impacts on effort motivation. In situations where effort avoidance lacks negative consequences (e.g., in laboratory settings), individuals may avoid failure by not exhibiting any achievement behavior and thus prevent the risk to fail. However, in many instructional contexts, students who do not invest sufficient effort and time for learning will face severe consequences such as failing the examination. The severity and unpleasantness of these consequences outweigh negative feelings in the preparation phase and the examination. In that case, anxiety strengthens positive extrinsic achievement-related effort motivation by the intention to avoid failure (Pekrun, 1988). Students with high degrees of statistics anxiety may experience debilitating levels of anxiety in the examination, but they should be motivated to invest effort in the examination preparations and to show appropriate learning behaviors for the examination. Thus, negative effects in the examination due to worry and rumination can be outweighed by enhanced effort in the preparation phase. In that sense, one could regard statistics anxiety as a "blessing in disguise." Birenbaum and Eylath (1994, p. 96) also explain zero-correlations in their study with the assumption "students with high levels of statistics anxiety may have worked harder and suffered more in order to earn the same grade as their less anxious counterparts."

Expectancy-value theory also explains results such as significant correlations between statistics anxiety and performance in difficult and zero-correlations in easier examinations (Keeley et al., 2008): When students judge their chances for success positively (in not too difficult examinations) they are more willing to invest effort and time. Similarly, students with a positive self-concept in statistics rate their chances to succeed positively (and most probably also have a higher prerequisite knowledge) and are more likely to exhibit effective learning behaviors.

Conclusions

Taken together, these results suggest that the influence of statistics anxiety may differ over the course of learning, with prior positive influences and negative influences of state anxiety in the examination. Future research should take such two-fold effects into account and investigate the influence of statistics anxiety within a framework of variables and within a longitudinal design, creating the possibility for effective teaching interventions. Depending on factors such as the self-assessment of their abilities, the importance of a course, expectancies of failure and its consequences, anxiety may reduce or enhance motivation. Furthermore, there is a lack of studies that investigated the immediate effects of anxiety in an examination together with antecedents and consequences of anxiety. Research designs are recommended that take these variables and their long-term interactions into account.

Author Contributions

All authors of this article fulfilled the four requirements listed in "Frontiers of Psychology" (http://journal.frontiersin.org/journal/psychology#author-guidelines):

- Substantial contribution to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- Drafting the work or revising it critically for important intellectual content; AND
- Final approval of the version to be published; AND
- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 02 June 2015
doi: 10.3389/fpsyg.2015.00742

Metacognition and confidence: comparing math to other academic subjects

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Two studies addressed student metacognition in math, measuring confidence accuracy about math performance. Underconfidence would be expected in light of pervasive math anxiety. However, one might alternatively expect overconfidence based on previous results showing overconfidence in other subject domains. Metacognitive judgments and performance were assessed for biology, literature, and mathematics tests. In Study 1, high school students took three different tests and provided estimates of their performance both before and after taking each test. In Study 2, undergraduates similarly took three shortened SAT II Subject Tests. Students were overconfident in predicting math performance, indeed showing greater overconfidence compared to other academic subjects. It appears that both overconfidence and anxiety can adversely affect metacognitive ability and can lead to math avoidance. The results have implications for educational practice and other environments that require extensive use of math.

Keywords: metacognition, math anxiety, math education, confidence

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *20 February 2015*
Accepted: *18 May 2015*
Published: *02 June 2015*

Citation:
Erickson S and Heit E (2015) Metacognition and confidence: comparing math to other academic subjects. Front. Psychol. 6:742. doi: 10.3389/fpsyg.2015.00742

Introduction

Two components of metacognition are particularly relevant for successful learning: self-monitoring, e.g., assessing performance, and self-regulation, e.g., choosing what and how to study (Nelson and Dunlosky, 1991; Thiede et al., 2003; Metcalfe, 2009). Metacognition has been found to be crucial for calibration of self-knowledge of ability (Schunk and Ertmer, 2000; Sperling et al., 2004), in domains and tasks such as mathematics (Pugalee, 2001), science (Schraw et al., 2006), reading (Pressley, 2002), and writing (Pugalee, 2001). If people are unable to assess their performance accurately, then it is unlikely that they will be able to learn optimally (see Townsend and Heit, 2011, for a related argument). Any improvements in metacognition would allow learners to better judge what they know and how well they will be able to learn information and recall it later.

Our focus in the present research is self-monitoring in math. In addressing the topic of metacognition and math, it is important to consider whether metacognition is domain-general or domain-specific. In other words, to what extent are there general points to be made about people's metacognitive abilities, potential for error, and underlying mechanisms across subject domains, and to what extent are there distinctive points to be made for particular domains? Do the difficulties that learners face with math reflect general issues with metacognition, or something special about math?

Though there is ongoing debate on whether metacognition is domain-specific or domain-general, there is no debate on the importance of metacognition in any learning process. In this paper we will focus primarily on possible differences between metacognition in mathematics learning when compared to other domains, as math anxiety can affect both domain performance and metacognitive performance.

Based on past research, it remains unclear whether metacognitive performance is similar across domains. Metacognition research typically addresses a single subject domain in isolation, and those few studies comparing metacognition across domains have shown mixed results (e.g., Veenman et al., 2006). Though these past studies have used varying methodologies and assessments for measuring metacognition, results still bear on this issue of domain generality versus specificity and provide two views which we must consider.

Domain-General Views of Metacognition

Some studies support domain generality of metacognition, treating it as a skill that can be applied across different content areas (e.g., Schraw, 1996; Halpern, 1998; Veenman and Verheij, 2001). In these cases, domain-general metacognitive skills are distinguished from domain-specific knowledge. This framework assumes that cognitive skills can be domain-specific whereas metacognitive skills can be applied across even unrelated domains. Interestingly, metacognitive ability appears unrelated to IQ (Alexander et al., 1995). Rather, metacognitive skills are assumed to improve along with domain knowledge.

Metacognitive skills are further related to domain knowledge in that metacognitive skill can aid learners those with low ability or knowledge. For instance, Swanson (1990) showed that metacognitive ability compensated for IQ in a comparison between fifth and sixth grade student problem solving ability. Ability to solve problems was unrelated to IQ, while those with higher metacognitive ability were better able to solve problems than those with lower metacognitive ability. This result suggests that metacognition can be applied flexibly across tasks and thus is a domain-general skill.

This domain-general view of metacognition is consistent with the unskilled and unaware phenomenon, in which people show domain-general overconfidence in their abilities, with low performers showing greater overconfidence than higher performers (Kruger and Dunning, 1999; Dunning et al., 2003). This phenomenon has been shown for students predicting performance on laboratory tests ranging from logical reasoning to grammatical knowledge and sense of humor. Studies with academic content in classroom settings also exhibit this phenomenon (Maki and Berry, 1984; Miller and Geraci, 2011). Miller and Geraci (2011) also demonstrated that the lowest performers were overconfident in exam score predictions, but they were also less confident in these predictions than were the highest performers. Thus, although the unskilled might be more aware than once thought, they still demonstrate overconfidence nonetheless. Furthermore, while people with high performance might demonstrate slight underconfidence, people with lower performance have even more exaggerated overconfidence. From this, one might predict that students who are struggling in math are particularly overconfident.

Domain-Specific Views of Metacognition

In contrast, some investigations of individual differences in metacognition point toward domain specificity. For example, Kelemen et al. (2000) found that metamemory accuracy was task specific for university students. They tested memory monitoring performance across four metacognitive tasks: ease of learning judgments for Swahili-English word pairs, feeling of knowing judgments for general knowledge questions, judgments of learning for unrelated English word pairs, and text comprehension monitoring for narrative texts. While they found individual differences in memory and confidence that remained constant across tasks, individual differences in metacognitive accuracy changed for each task. Glaser et al. (1992) provided evidence that metacognition can differ based on task. They found that metacognitive strategies of university students varied across discovery learning tasks. In their comparison of several reasoning tasks, they further found variability in metacognitive performance for components of problem solving. There are a variety of alternative but equally successful problem solving strategies and a variety of metacognitive approaches for these problems. In general, successful problem solvers use metacognitive strategies more often than less successful problem solvers, but there is no one set of metacognitive strategies that led to successful problem solving. They also found that domain content and context led to variation in use of metacognitive strategies, and that particular metacognitive skills were associated with specific learning success or failure within particular domains and contexts.

Still others have suggested that metacognition might be domain-specific early in development, beginning as reflective self-analysis of cognition. For example, Paris and Byrnes (1989) suggest that such self-directed reflection develops in children as self-corrections, and this behavior becomes more prominent as children get older. As children develop self-regulation for individual tasks, then gradually learn to apply general self-correction skills across a variety of tasks. Similarly, Karmiloff-Smith (1992) suggested that this reflection results in the restructuring of self-knowledge that increases theoretical understanding of one's cognition. This restructuring starts to differentiate and separate various domains of knowledge. Both these views support a theory of first domain-specificity of metacognition that eventually extends to be a domain-general skill. Then as metacognitive skill improves, this skill can be applied across a variety of domains. Veenman and Spaans (2005) provided evidence for this in their findings of first domain-specificity in metacognitive skill in the first year of high school then domain generality later for third year high school students. First-year and third-year students solved math problems while thinking aloud and also performed an inductive learning biology task. Metacognitive skillfulness was measured based on enactment of metacognitive behaviors (e.g., entirely reading a problem statement, selection of relevant information needed to solve the problem, monitoring the on-going problem-solving process, checking the answer, reflecting on the answer). A difference in metacognitive skillfulness was observed when comparing the two groups of students in that metacognitive skills are at first domain-specific for first-year students, while they are domain-general for third-year students.

Previous research shows connections between metacognition and math anxiety. Math anxiety (or math phobia) is a fear of math that leads to math avoidance or lower math performance (Ashcraft, 2002; Ashcraft and Krause, 2007). This sometimes extreme anxiety is harmful in both educational and workplace settings (Meece et al., 1990; Furner and Berman, 2003). Performing math tasks in stressful situations, such as during tests, only compounds math anxiety (Beilock and Carr, 2005; Beilock, 2008). This anxiety can start early in children's education, with elementary school students already showing harmful effects of math anxiety on their math achievement (Ramirez et al., 2013). Math anxiety interrupts cognitive processing through its interference with working memory, and this is what can cause people to show lower performance under pressure (Beilock and Carr, 2005). While math anxiety does not appear to affect simple math tasks such as single digit addition, it does affect decision-making processes for number sense and any task that required procedural aspects of arithmetic (Dehaene, 1997; Ashcraft, 2002). The tasks requiring use of working memory are adversely affected by math anxiety. Students who are highly math anxious tend to make more errors in timed problems than did those with low math anxiety. This is also consistent with Eysenck and Calvo's (1992) model of general anxiety effects, in which general anxiety disrupts working memory through preoccupation with thoughts and attention given to worry instead of to the current task. This preoccupation is a second task that places a heavier load on working memory, a component of cognition that is used in metacognition (Shimamura, 2000).

The widespread evidence for math anxiety suggests the view that math may be uniquely problematic compared to other academic subjects. There does not seem to be a corresponding body of evidence for, say, literature anxiety or even biology anxiety. Generalizing this point, we would expect that if students fear math, then they should generally have low confidence in math compared to other subjects and a corresponding difference in metacognitive ability. Indeed, Ashcraft (2002) found evidence for this point in terms of strong negative correlations between math anxiety and self-confidence in math.

Overview of Experiments

Accounts of domain specificity are consistent with the idea that math is uniquely problematic. Contrasting this view that math is unique are accounts of domain generality, including the unskilled and unaware phenomenon. So are students underconfident in math, as would be expected from the math is unique view, or are students overconfident in math, as would be predicted by the unskilled and unaware view? Note that we present these as opposing views, but the predictions from these views were derived by ourselves.

Our purpose is not to examine whether math-phobic students are less confident than non-math-phobic students or whether students are less confident in math than in other subjects. Rather, we focus on calibration of metacognitive judgments, that is, whether students are under- or over-confident relative to their performance. In addition to general measures of calibration, we also compared calibration across academic subjects. We assessed both absolute calibration, in which we simply measure how well subjective scores matched objective scores, as well as relative calibration, assessing whether participants with higher subjective scores had correspondingly higher objective scores. Other than looking at confidence for students with lower versus higher scores, it was not our aim to examine individual differences.

In two studies, we assessed confidence in math as well as other academic subjects (biology, literature). These studies were conducted based on approval by the Institutional Review Board (IRB) for our institution (University of California, Merced). High school (Study 1) and college (Study 2) students took standardized tests and estimated their performance. Following the view that math is unique, we would expect underconfidence in math relative to the other subjects and likely worse metacognitive calibration. In contrast, following the unskilled and unaware view, we would expect similar overconfidence in math compared to other subjects. In Study 2, we included a standard measure of math anxiety. We note again that it was not our purpose to examine individual differences in anxiety but rather to look at students who were most likely math anxious overall, and in general our findings are limited to the groups we studied.

Study 1

Method

Participants in this study attended a summer program at a diverse public high school in California. They made two estimates: predictions (before each test) of their performance as well as postdictions (after each test). Mutiple choice tests were adapted from teachers' materials used at that grade level in this school, giving students a basis for making predictions, with even more information when making postdictions.

Our main focus was to compare calibration of estimates about math to the other two subjects. We also compared predictions to postdictions, allowing us to determine if metacognitive judgments improved after completing a test, as would be expected from previous research (Kruger and Dunning, 1999; Dunning et al., 2003).

Participants

There were 40 participants (25 female, 15 male). All were students (*mean age* = 15.27, SD = 0.55) at Central Valley High School in Ceres, California, who took the study for extra credit in their summer school class (Algebra 1). A majority of these students had failed math the previous academic year. Ceres Unified School District is located in a rural area; its student population is 72% Hispanic-Latino, 21% White-Caucasian, 3% Asian-Pacific Islander, 1% African American, and 3% of other ethnicity.

Materials and Procedure

Each participant took three computer-based tests (biology, literature, mathematics, in randomized order), each test consisting of 15 questions with 15 min allowed per test. Questions were normed so that the overall level of difficulty across tests was comparable, to avoid ceiling and floor effects and to assure variance in scores. Questions left unfinished within the allotted time were scored as incorrect. Participants were told that these tests were similar to those from their current classes. Question style was multiple choice with five answer choices. Before each test, participants provided a predicted score (number of questions correct) for how well they would do. After each test, participants provided a postdicted score for how well they thought they had performed. They were not told their actual scores.

Results and Discussion

Key descriptive results are in **Figure 1**. The leftmost bar for each category represents average predicted score, the middle bar represents average actual test score, and the rightmost bar represents average postdicted score. The general pattern is that predictions are substantially greater than actually performance, and postdictions are somewhat greater than actually performance. This overconfidence is particularly striking for predictions about math performance. We do not show breakdown by gender, however, predicted, actual, and postdicted scores averaged about 10% higher for males.

First, we examined predictions in a three-way, predicted versus actual score × academic subject × gender, ANOVA. There was a significant main effect of predicted (*mean* = 61.7) versus actual (*mean* = 43.0) score, $F(1,38) = 54.45$, $MSE = 6.00$, $\eta^2 = 0.59$, $p < 0.0001$, indicating overconfidence in predictions. The academic subject variable did not reach statistical significance, $F(2,152) = 4.14$, $MSE = 4.11$, $\eta^2 = 0.05$. However, there was a significant predicted versus actual score × academic subject interaction, $F(2,152) = 10.31$, $MSE = 4.11$, $\eta^2 = 0.11$, $p < 0.0001$, implying that overconfidence differed by academic subject. Notably, participants showed the highest degree of overconfidence in mathematics (*predicted score* = 62.0, *actual score* = 38.9). There was also a main effect of gender, $F(1,38) = 5.88$, $MSE = 17.41$, $\eta^2 = 0.13$, $p < 0.05$, but remaining interaction terms were not statistically significant, $F < 1$. Hence, degree of overconfidence did not depend on gender, although it may be that the sample size did not yield enough power to fully address this point.

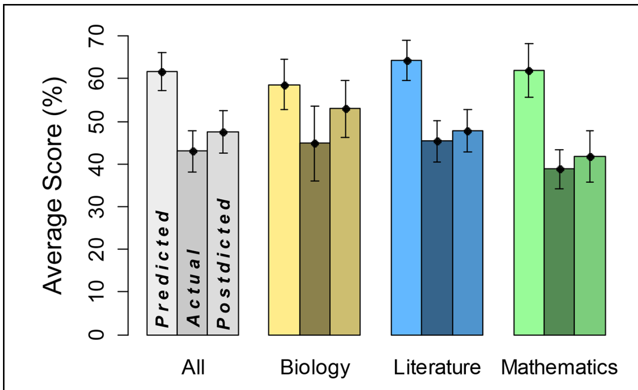

FIGURE 1 | Predicted, actual, and postdicted scores by domain. Leftmost bars represent predicted scores, middle bars domain performance, and rightmost bars postdicted scores, each with SE.

We also conducted a comparable analysis on postdicted scores (*mean* = 47.5). In this three-way ANOVA, there was a significant effect of academic subject, $F(2,152) = 21.00$, $MSE = 4.06$, $\eta^2 = 0.21$, $p < 0.0001$. Note that biology had the highest values overall and mathematics had the lowest. There was also a significant main effect of gender, $F(1,38) = 5.10$, $MSE = 19.74$, $\eta^2 = 0.12$, $p < 0.05$. The remaining main effect and interaction terms were not statistically significant, $F < 1$. Hence, we did not see significant overall overconfidence on postdictions, and overconfidence did not depend on academic subject or gender.

The preceding analyses focused on absolute calibration, namely how well subjective scores matched objective scores, on average. We next examined relative calibration, namely whether participants with higher subjective scores had correspondingly higher objective scores, measuring relative calibration in terms of correlation coefficient, r, across all participants (**Table 1**). Relative calibration is particularly strong for math, and particularly weak for literature, with biology falling between.

Correlations of estimates of performance were not significant across domains, suggesting that student metacognition was not domain-general. We also tested differences in correlations both across domain and within domain. Steiger z-tests of independent correlations showed that the prediction versus actual score correlations are significantly different between math and literature ($z = 2.28$, $p < 0.02$). Similarly, postdiction versus actual score correlations are significantly different between math and literature ($z = 2.36$, $p < 0.02$). Williams t-tests of dependent correlations reveal that differences between prediction versus actual score and postdiction versus actual score are significant for all of biology ($t = -3.19$, $p < 0.0029$), literature ($t = -3.13$, $p < 0.0034$), and math ($t = -2.28$, $p < 0.028$). Thus calibration significantly improved in postdictions on all tests when compared to calibration of predictions.

Linear regression calibration curves also illustrate this point (**Figure 2**). Regression lines that more closely follow the main dashed line (perfect calibration) indicate better metacognitive calibration for that academic subject. Regression lines for biology and literature are shallow, showing little sensitivity to actual performance. These lines show the usual unskilled and unaware pattern of overconfidence at the lowest level of performance and underconfidence at the highest level (Kruger and Dunning, 1999; Dunning et al., 2003). Calibration for math in this case seems to take unskilled and unaware one step

TABLE 1 | Correlations between participant-produced estimates and performance by domain.

	Biology	Literature	Math
Prediction versus actual score	0.32*	0.10	0.56***
Postdiction versus actual score	0.39*	0.21	0.64***

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$ (as compared to 0).

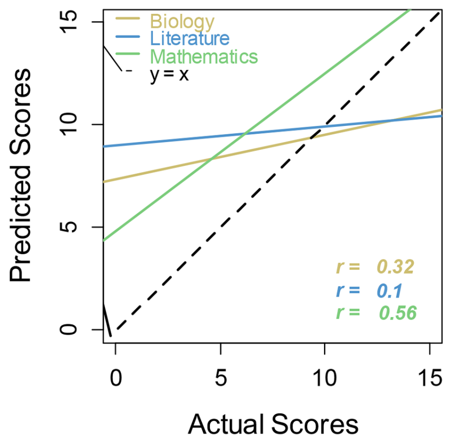

FIGURE 2 | Regression lines for actual versus predicted scores by academic subject. Regression lines that more closely follow the main dashed line (perfect calibration) indicate better metacognitive calibration for that academic subject.

further, in that even the high performers over-estimated their ability.

In general, results more closely supported the unskilled and unaware view rather than the math is unique view. Students were generally overconfident in all three academic subjects, at least on predictions if not postdictions. The only evidence we found suggesting a difference for math is that relative calibration for math was actually the best and overconfidence was the greatest. Overall performance was somewhat lower for female students than for males, but so were predictions and postdictions, so their overconfidence was no different.

Study 2

We turn to another study, attempting to replicate and extend key findings from Study 1, which might have been due to idiosyncrasies of the particular student sample or test instruments used. In Study 2, we conducted a similar study on college students, using sample SAT test questions. We would have expected high school students in Study 1 to be math anxious, because most high school students show some math anxiety (Hembree, 1990; Ma, 1999; Maloney and Beilock, 2012), and most of the students in our study had previously failed math classes. In Study 2, we included a standard measure of math anxiety adapted from a shortened Math Anxiety Ratings Scale (MARS, Alexander and Martray, 1989). Although we did not directly measure math anxiety for students in Study 1, we replicated this study within the same school population the following summer, and the average shortened MARS score was 77. This study also included additional measures but otherwise replicated findings from the high school study presented here. For comparison, Ashcraft and Moore (2009) found an average shortened MARS score of 61 across several college samples identified as math anxious.

Method

Participants

There were 46 participants (28 female, 18 male) in this study. All were UC Merced undergraduates (*mean age* = 19.96, SD = 1.75) who received extra credit in their introductory psychology or cognitive science classes for their participation. The UC Merced undergraduate population is 40% Hispanic-Latino, 29% Asian-Pacific Islander, 17% White-Caucasian, 7% African American, and 7% other ethnicity.

Materials and Procedure

Participants took three tests (biology, literature, mathematics), each with 15 questions. Again, questions left unfinished within the allotted time were scored as incorrect. Participants were told that these were based on SAT II Subject Tests (which most students have taken). Students completed three assessments derived from past questions released by the College Board, making predictions and postdictions as in Study 1. Test questions were normed to avoid ceiling and floor effects. Then, participants answered 23 questions about math anxiety from a variant of the shortened MARS (Alexander and Martray, 1989), using a rating scale ranging from 1 – "no anxiety" to 5 – "very high anxiety," with possible scores from 23 to 115. (We dropped two of three questions from the standardized shortened MARS with nearly identical wording).

In pilot studies, in an effort to design tests of equal difficulty, items of comparable difficulty for each test were selected using individual question ratings (easy, medium, difficult) provided by College Board. However, performance floor effects on the pilot math tests were so pronounced that easier questions were substituted in an effort to bring average performance closer to the level as the literature and biology tests.

Results and Discussion

The results largely replicated Study 1 (see **Figure 3**), most notably in terms of general over-confidence of predictions compared to actual scores, most notably for math.

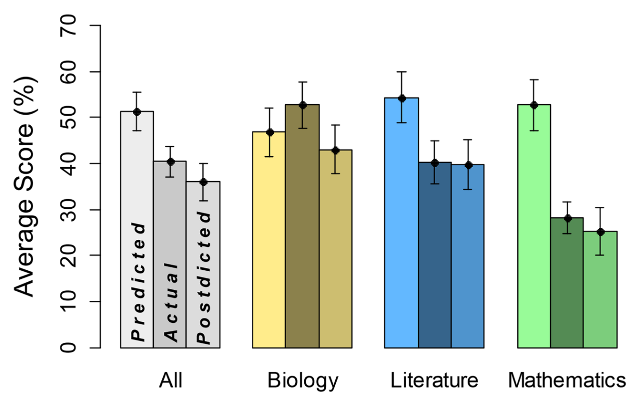

FIGURE 3 | Predicted, actual, and postdicted scores by domain. Leftmost bars represent predicted scores, middle bars domain performance, and rightmost bars postdicted scores, each with SE.

In a three-way, predicted versus actual score × academic subject × gender ANOVA, there was a significant main effect of predicted (*mean* = 51.3) versus actual (*mean* = 40.4) score, $F(1,44) = 19.70$, $MSE = 9.31$, $\eta^2 = 0.31$, $p < 0.0001$, indicating overconfidence in predictions. There was also a significant main effect of academic subject, $F(2,176) = 7.19$, $MSE = 4.18$, $\eta^2 = 0.09$, $p < 0.0001$; scores were lowest overall in math. There was a significant interaction between these two variables, $F(2,176) = 29.58$, $MSE = 4.18$, $\eta^2 = 0.22$, $p < 0.0001$, indicating that degree of overconfidence depended on academic subject. Overconfidence was greatest in mathematics (*predicted score* = 52.8, *actual score* = 28.3), however, we are careful not to over-interpret the interaction because actual scores also differed by academic subject. The remaining main effect (gender) and interaction terms were not statistically significant, $F < 1$. Hence, the finding of overconfidence, particularly in math, did not depend on gender.

We also conducted a comparable analysis on postdicted scores (*mean* = 36.0) and actual scores. This ANOVA revealed a main effect of postdicted versus actual score, $F(1,44) = 4.48$, $MSE = 6.85$, $\eta^2 = 0.09$, $p < 0.05$, indicating that participants were slightly yet significantly underconfident overall. With that said, given the overall drop from predictions to postdictions, we see this as reflecting that participants were better calibrated after taking the test, as in Study 1. (A third ANOVA comparing predicted and postdicted scores showed a main effect of predicted versus postdicted.) There was a main effect of academic subject, $F(2,176) = 37.52$, $MSE = 3.70$, $\eta^2 = 0.41$, $p < 0.0001$. There was also a significant interaction between academic subject and postdicted versus actual score, $F(2,176) = 3.12$, $MSE = 3.70$, $\eta^2 = 0.02$, $p < 0.05$, indicating a difference in overconfidence by academic domain. Though all medium and difficult questions were removed and replaced with easy ones (based on College Board question ratings), performance remained lower for the math test compared to the other two subjects. The remaining main effect (gender) and interaction terms were not statistically significant, $F < 4$. Even after replacing all questions with those rated as easy by the College Board, and thus creating a minimally difficult assessment that incorporated actual SAT questions, math test scores were consistently lower than biology or literature test scores. Analyses were also conducted using a sample of these math questions by selecting seven questions that participants scored best on. However, this did not change our findings. Again as in Study 1, the finding of overconfidence, particularly in math, did not depend on gender.

Analyses of relative calibration (**Table 2**, **Figure 4**) yielded results similar to Study 1. Correlations between predicted and

TABLE 2 | Correlations between participant-produced estimates and performance by domain.

	Biology	Literature	Math
Prediction versus actual score	0.01	0.12	0.47***
Postdiction versus actual score	0.41**	0.38**	0.35*

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$ (as compared to 0).

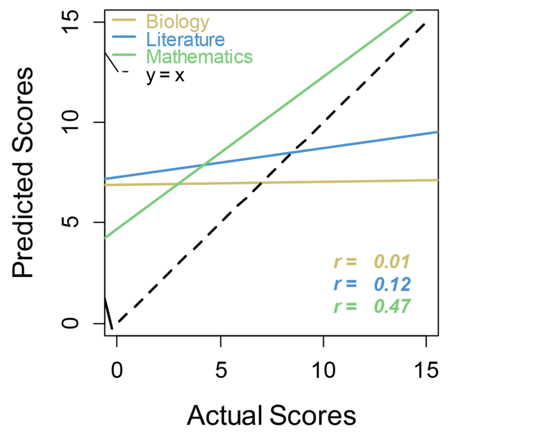

FIGURE 4 | Regression lines for actual versus predicted scores by academic subject. Regression lines that more closely follow the main dashed line (perfect calibration) indicate better metacognitive calibration for that academic subject.

actual scores were highest for math, although, based on a Steiger *z*-test of independent correlations, there was only a significant difference in correlations between predicted and actual score for biology and predicted versus actual score for math ($z = 2.32$, $p < 0.02$). Correlations for postdicted scores were approximately the same for all three academic subjects, and there were no significant differences among these correlations. Williams *t*-tests of dependent correlations reveal that there were significant differences in predicted versus actual and postdicted versus actual correlations for both literature ($t = -3.21$, $p < 0.0025$) and biology ($t = -3.82$, $p < 0.00042$). Thus calibration was significantly different before and after the test for both literature and biology. However, this pair of correlations for math showed no significant difference, hence there was a lack of evidence for improved calibration in math. Again, the regression lines for biology and literature showed overconfidence at the lowest level of performance and underconfidence at the highest level, revealing again the general unskilled and unaware pattern. In contrast, students were simply overconfident in general for math.

Students were clearly math anxious overall, with an average adapted shortened MARS score of 73/115 (SD = 16.8). Comparatively, Ashcraft and Moore (2009) found an average MARS score of 61/125 using a test instrument with two more questions, across several college samples identified as math anxious. Further analyses suggested that more anxious participants had lower performance and lower levels of overconfidence; however, inferential tests did not reach statistical significance. Therefore we simply conclude that students generally experienced math anxiety. We measured a Cronbach's alpha of 0.94 for the version of the shortened MARS math anxiety that we used, indicating very good internal consistency. This is comparable to the Cronbach alphas Plake and Parker (1982) found for the original full-length 98-question MARS instrument ($\alpha = 0.97$) as well as the shortened 24-question version MARS-R ($\alpha = 0.98$).

Overall, the results were consistent with the unskilled and unaware view, in that there was global overconfidence in predictions across subject domains. The finding that even the students who performed best in math were overconfident (see **Figure 4**) is not consistent with unskilled and unaware, however. Instead of observing underconfidence in the best performers, as has typically been displayed by the unskilled and aware phenomenon, we see persisting overconfidence even in the highest performing participants. In terms of math being unique, it was unique here in the sense that overconfidence was the greatest and metacognitive calibration was the best. Neither of these results would be predicted from the idea that anxiety is particularly high for math.

General Discussion

Our basic conclusion is that students aligned in some ways to both the unskilled and unaware phenomenon and the idea that math is unique. In both studies, students over-estimated their performance in their predicted scores for all domains, though their calibration did improve for postdictions. This provides support for the domain generality of metacognition under the unskilled and unaware view. Interestingly, the most exaggerated over-confidence was observed for math, which supports the view that math is unique and that metacognition is domain-specific. What is novel about these results is that students appear to be math anxious yet also overconfident in math. In addition, relative calibration of metacognition for math was generally better than other academic subjects. This overconfidence and greater metacognitive calibration replicated in both studies in this paper, and has also been consistent across our earlier studies (Erickson and Heit, 2013). We have reliably documented over past studies that both high school and college students have over-predicted their scores on math tests, along with biology and literature tests.

Math is indeed unique in some respects and this manifests in an interesting way. Rather than showing lower confidence in math compared to other subjects and poorer metacognition, as would be expected based on the original view that math is unique, students generally showed the highest level of overconfidence in math compared other academic subjects. Students, rather than displaying differing metacognition in the form of lower confidence stemming from math anxiety, instead showed differing metacognition in the form of even more exaggerated overconfidence despite the presence of math anxiety. In Study 1, students were retaking only their Algebra 1 class, not a literature or a biology class. Whereas we did not directly measure math anxiety in this study, it is plausible that these students were math anxious overall.

Another relatively novel feature of these two studies is the consideration of both predictions and postdictions of performance, rather than just postdictions or individual test item evaluations. Math was unique in that students displayed higher over-confidence when compared to other subjects, and this persisted in both predictions and postdictions. Students also displayed elements of being unskilled and unaware both before and after the test, though their calibration did improve after taking a test. It seems an obvious result that metacognition would improve after students take a test, and it is tempting to treat postdictions as the more relevant measure to be considered when evaluating actual student metacognition. After all, doing so would help in comparing metacognition across students once they have equal footing in knowing exactly what is on the test. However, we would argue that predictions, not postdictions, provide a more realistic and practical measure of student metacognition. Students typically cannot view actual questions before they take a test in an academic setting. Rather, they must use predictions to guide their self-regulation activities, including studying as well as choices such as how to take notes in class (or even whether to attend class). Students' metacognitive skill in postdicting performance after a test might be more accurate, but this cannot help them to improve test performance and academic success.

As noted earlier, our findings are focused on the math-anxious student groups studied here, comparing academic subjects. We would see a comparison to non-math-anxious students as a fascinating but challenging potential topic for future research. Just assembling two groups of students who differ in terms of math anxiety but are equal on other variables would present considerable difficulty. Students who differ in math anxiety likely have other attributes (e.g., demographics, math ability) that also differ. These variables would have to be carefully teased apart in order to make any comparisons of math-anxious and non-math-anxious students.

Possible Mechanisms

It was not the purpose of these studies to find the exact mechanisms that underlie metacognitive function for math. In general, finding a similar pattern of results for two different tasks does not necessarily indicate that they are the same mechanistically. However, theories in the math anxiety literature help explain why metacognition for math is unique when compared to other academic domains. Notably, Beilock (2008) along with others (Ramirez et al., 2013) has shown that working memory is compromised by math anxiety and also by stressful situations, providing a possible explanation for the reduced metacognitive ability we observed for math. Ashcraft and Krause (2007) further showed that math anxiety and peoples' preoccupation with this fear function as secondary mental tasks that draw on working memory resources necessary for problem solving. Any math problem solving that requires more than simple retrieval of information depends on working memory, so a reduction in working memory capacity can lead to a reduction in math performance. This lower performance then results in a disconnect between typical academic performance and math performance and a corresponding miscalibration in metacognition. People's metacognitive evaluation of math ability may ordinarily be more accurate when they are engaging in tasks in a less stressful environment but becomes less accurate when put under pressure.

So far, we have demonstrated overconfidence as a flaw in self-monitoring about math and other domains. Self-monitoring strategies such as self-testing give learners specific and measureable feedback about how much they know. Without accurate feedback, learners are unable to select appropriate self-regulation strategies to further their learning process (Dunlosky et al., 2005). Rather, they choose study strategies based on feelings of knowing and judgments of learning, both of which have been shown to be inaccurate self-measures of knowledge (Metcalfe and Finn, 2008). These inaccurate measures lead to student flaws in identifying problem areas of knowledge. Without knowing what they do not understand, learners are unable to make plans to fill in gaps in their knowledge. Students can benefit from using effortful self-monitoring by enacting practice tests at home, where they might not suffer as much detraction from working memory stores. With less stress from a testing environment, they will be able to perform closer to their actual knowledge level. This enables learners to highlight gaps in their knowledge and use this to organize their study time more effectively.

Possible Limitations

We do not know to what extent these findings generalize to other populations. Both UC Merced and Central Valley High School are both in the same rural area of California and are not necessarily representative of all learners. Ideally, additional studies will be conducted in other learning settings and with more widely differing populations. For instance, populations representing a full spectrum of math anxiety would provide a more complete picture for the relationship between math anxiety and metacognition, though such research would also need to be take account of general anxiety, math ability, and other variables related to math anxiety and metacognition.

Students in Study 2 were math anxious, and although we did not directly measure math anxiety in Study 1, a later study identified another sample of the same high school population as math anxious using the same MARs measure. From this, we might assume that the students in Study 1 had a similar level of math anxiety. Although we did not include a measure of general anxiety, it is also possible that the populations here had general anxiety and not just math anxiety. Presence of generally high anxiety would further compromise working memory and, consequently, metacognitive ability.

Although performance was not exactly the same across academic subjects, it does not appear that the exaggerated overconfidence in math was simply result of choosing intrinsically more difficult test items compared to biology and literature. Questions in both studies were normed for difficulty, and the math test in Study 2 was in fact less difficult than either biology or literature, based on test item difficulty ratings provided by the College Board, creators of the standardized test. Furthermore, analyses that included only those questions that participants performed best on still displayed this finding of exaggerated overconfidence. In an effort to improve the realism of this study, a later version of this study was performed in math classes at UC Merced. Students provided predictions and postdictions for class midterms, thus utilizing a much more realistic assessment than an SAT II test taken in a lab setting. Findings generally replicated those from the studies in this paper, so results in this paper were not an artifact of lab setting or the particular assessments used.

Final Remarks

We do not doubt that math anxiety exists. However, it is important to differentiate metacognitive judgments of performance from feelings of anxiety, which may have a more emotional or physical, rather than cognitive, basis. That students can be anxious yet overconfident has pernicious implications for struggling math learners. Overconfidence and anxiety provide students with two reasons to avoid studying math or attending math classes. According to models of metacognition, learners stop studying when believe they have reached mastery (Son and Sethi, 2010). Furthermore, extensive evidence shows that anxiety leads to avoidance (Ashcraft, 2002), implying that anxious students would avoid attending math classes. Other examples of math avoidant behaviors include avoiding lectures, avoiding homework, avoiding study time, or avoiding test preparation. Globally, the 2012 Programme for International Student Assessment (PISA) study, which assessed 15–16 year olds in 65 countries, found that students with higher math anxiety were more likely to have lower math self-concept. Trends in this comprehensive study point toward increases in math anxiety over the past decade.

Metacognition can also further impact other abilities such as attention, memory, perception, comprehension, reasoning, and problem solving (Kitchener, 1983; Metcalfe and Shimamura, 1994) and also affect social behavior (Jaccard et al., 2005) and decision making (Cohen et al., 1998). We have not yet examined the effects of math confidence on math anxiety on self-regulation. Which is a better predictor of study behavior, math confidence or math anxiety? Would pointing out the contradiction between being overconfident about math and being anxious about it have beneficial consequences for struggling students? We see these questions as important for future research.

We finish with a cautionary note. Some educational interventions aim to boost students' math self-confidence, because math self-concept is strongly related to math grades (Marsh et al., 2006). It is important to keep in mind that students' confidence in their math performance is probably already high, likely contributing to math avoidance. Aiming to further increase self-confidence in math may have unintended consequences for learning.

Acknowledgments

This study is based upon work while Evan Heit was serving at the National Science Foundation (US). Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 14 October 2015
doi: 10.3389/fpsyg.2015.01543

The role of self-math overlap in understanding math anxiety and the relation between math anxiety and performance

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Recent work has demonstrated that math anxiety is more than just the product of poor math skills. Psychosocial factors may play a key role in understanding what it means to be math anxious, and hence may aid in attempts to sever the link between math anxiety and poor math performance. One such factor may be the extent to which individuals integrate math into their sense of self. We adapted a well-established measure of this degree of integration (i.e., self-other overlap) to assess individuals' self-*math* overlap. This non-verbal single-item measure showed that identifying oneself with math (having higher self-math overlap) was strongly associated with lower math anxiety ($r = -0.610$). We also expected that having higher self-math overlap would leave one especially susceptible to the threat of poor math performance to the self. We identified two competing hypotheses regarding how this plays out in terms of math anxiety. Those higher in self-math overlap might be more likely to worry about poor math performance, exacerbating the negative relation between math anxiety and math ability. Alternatively, those higher in self-math overlap might exhibit self-serving biases regarding their math ability, which would instead predict a decoupling of the relation between their perceived and actual math ability, and in turn the relation between their math ability and math anxiety. Results clearly favored the latter hypothesis: those higher in self-math overlap exhibited almost no relation between math anxiety and math ability, whereas those lower in self-math overlap showed a strong negative relation between math anxiety and math ability. This was partially explained by greater self-serving biases among those higher in self-math overlap. In sum, these results reveal that the degree to which one integrates math into one's self – self-math overlap – may provide insight into how the pernicious negative relation between math anxiety and math ability may be ameliorated.

Keywords: math anxiety, math ability, math performance, self-math overlap, inclusion of other in self

OPEN ACCESS

Edited by:
Carlo Tomasetto, University of Bologna, Italy

Reviewed by:
Colleen Ganley, Florida State University, USA
Burkhard Gniewosz, Ludwig Maximilian University of Munich, Germany

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *22 June 2015*
Accepted: *24 September 2015*
Published: *14 October 2015*

Citation:
Necka EA, Sokolowski HM and Lyons IM (2015) The role of self-math overlap in understanding math anxiety and the relation between math anxiety and performance. Front. Psychol. 6:1543. doi: 10.3389/fpsyg.2015.01543

INTRODUCTION

Research on interpersonal relationships suggests that as close relationships develop, each member of the relationship begins to incorporate the other member into his or her sense of self, fostering a sense of 'self-other overlap' and leading to greater valuation of and commitment to their partner and the relationship (Aron et al., 1992; Agnew et al., 1998; Aron and Fraley, 1999).

Self-other overlap was originally conceptualized as a measure of interpersonal closeness between two members of a relationship. However, recent research has demonstrated that non-human and abstract entities, such as sports (Blanchard et al., 1998), nature (Schultz, 2001), consumer brands (Reimann et al., 2012; Trump and Brucks, 2012), and God (Hodges et al., 2013) can also be incorporated into one's sense of self in a manner similar to integrating another person into one's self, and can produce comparable effects. For example, individuals with high self-brand overlap are more likely to confuse attributes associated with a favorite brand with attributes associated with the self (Trump and Brucks, 2012), and individuals with high self-nature overlap are more likely to engage in behavior that benefits nature (Davis et al., 2009).

It is possible that some people highly value mathematics or view their interest and success in math as an integral part of who they are. In a cyclical process, integration of math into their sense of self may foster even greater valuation of and engagement in mathematics, akin to the way in which including a close relationship partner in the self enhances relationship development. Indeed, research examining the concept of math identification suggests that one's level of math identification (the degree to which individuals perceive math as self-relevant and important) can predict motivation to study for math exams (Smith and White, 2001) and greater likelihood of considering STEM careers (Smith et al., 2005). If individuals identify strongly with math, then their success in math should be a highly valued goal for which they are "self-evaluatively accountable" (Steele, 1997, p. 613), and failure in that domain should have important negative implications for one's sense of self-worth. Thus, in much the same way that including a close relationship partner in one's sense of self modifies an individual's perceptions of and behaviors toward the relationship, integrating math into one's self may produce distinct psychological and behavioral consequences for one's relationship with math. That said, most measures of math identification rely heavily on assessments of one's own math ability[1], whereas work from the self-other overlap literature indicates that various additional factors (e.g., perceptions of another's inclusion of you in their self, frequency of time spent together, etc.; Aron et al., 1992) contribute to the strength of a given self-other overlap rating. Because self-math overlap makes no presuppositions about perceptions of math achievement, it permits us to capture additional variance that might not be captured by self-report measures of math identification (e.g., those for whom math is particularly valued and personally relevant but who perceive that their math abilities are not especially strong).

Of particular interest in the current study is how one's inclusion of math in self relates to one's feelings of math anxiety. It is becoming increasingly evident that psychosocial factors play a key role in the experience of math anxiety (Meece et al., 1990; Pajares and Miller, 1994; Pekrun, 2006; Beilock et al., 2010; Ahmed et al., 2012). Furthermore, people who value math tend to experience less math anxiety (Hembree, 1990; Meece et al., 1990), and implicit measures of math identification are associated with implicit anxiety toward math (Nosek and Smyth, 2011). Here, we adapted a widely used measure of self-expansion in close relationships, the Inclusion of Other in Self Scale (IOS; Aron et al., 1992), to assess the extent to which an individual's cognitive representations of math and self are overlapping (a measure we call 'self-math overlap'; see **Figure 1**).

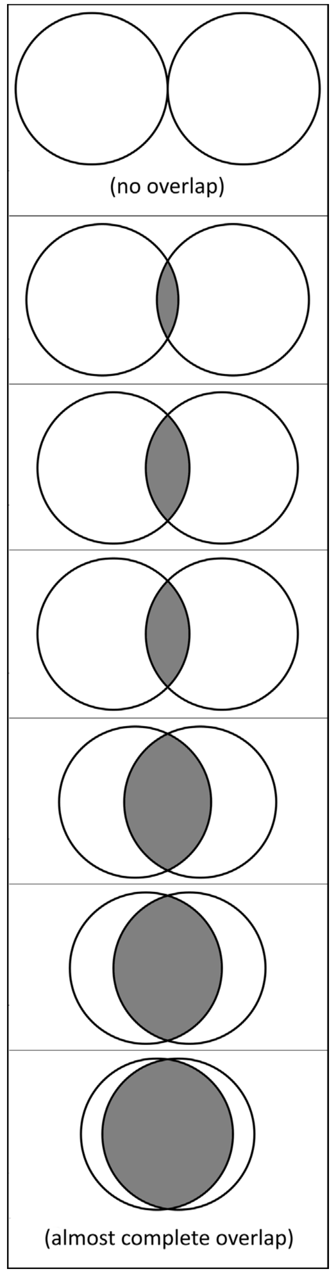

FIGURE 1 | The Self-Math Overlap measure. Participants selected the item which best represented their relationship with mathematics, where one circle represented their self (i.e., "You") and the other circle represented mathematics.

[1]Typical items include "I have always done well in math" and "I am good at math" (Spencer et al., 1999; Smith and White, 2001); for a recent and interesting exception, see Cribbs et al. (2015).

This simple measure takes less than a minute to complete, and its visual nature potentially lends itself to use in a wide range of settings and participants. Drawing from theories of interpersonal relationship development, domain identification, motivation, and math anxiety, we hypothesized that individuals who integrate math into their sense of self (e.g., have higher self-math overlap) would value math more and would also report lower levels of math anxiety using a traditional and widely used math anxiety scale (sMARS; Alexander and Martray, 1989).

However, in addition to these psychosocial factors, cognitive factors also contribute to math anxiety. It is well known, for instance, that there exists a persistent negative relation between poor math skills (a cognitive factor) and high math anxiety (for a review, see Ashcraft and Ridley, 2005). Furthermore, one's math achievement, one's beliefs about one's math abilities, and genetic factors associated with math problem-solving skills are predictive of math anxiety (Ma and Xu, 2004; Goetz et al., 2013; Wang et al., 2014). Understanding the psychosocial factors that modulate the strength of the association between math performance and math anxiety and how they do so is critical for decoupling this pernicious negative cycle. An individual's degree of self-math overlap may be one such factor. If math is an important part of the self (i.e., self-math overlap is higher), then being 'good' at math should be important for maintaining self-integrity, or the belief that the self is good, virtuous, and able to control important life outcomes (Steele, 1988; Sherman and Cohen, 2006). An individual who values but is unable to perform well in math may develop negative self-evaluations and view himself as inadequate, incapable, or otherwise flawed. Conversely, an individual for whom math is not integrated into self should exhibit fewer self-evaluative concerns while doing math and thus poor math performance should minimally threaten perceptions of self-integrity. Yet the way that individuals potentially deal with the threat to self-integrity (or relative lack thereof) of being 'bad' at math is unclear.

One possibility is that those higher in self-math overlap succumb to the threat to their sense of self of poor math performance[2], such that the negative relation for these individuals between math performance and math anxiety might be exacerbated. From this point of view, threat of math failure among individuals with higher levels of self-math overlap (and the ensuing damage that such math failure might do to their perceptions of self) might be especially acute. Indeed, evidence suggests that in the presence of negative stereotypes about one's math abilities (i.e., stereotype threat), women who strongly identify with math exhibit impaired math performance (Steinberg et al., 2012). Both stereotype threat and math anxiety are thought to predict poor math performance in part because the worries and distraction related to the experience of the threat or anxiety consume valuable cognitive resources that are necessary to successfully complete the task (Hopko et al., 1998; Schmader and Johns, 2003; Ashcraft and Krause, 2007; Beilock and Gray, 2007; Beilock et al., 2007). This distraction or worry appears to be exacerbated – at least in the case of stereotype threat – by strongly identifying with the domain in which one's performance is negatively evaluated (Steinberg et al., 2012). In a similar vein, it is possible that individuals with higher self-math overlap would also be most susceptible to the cognitively depleting effects of math anxiety. From this perspective, individuals higher in self-math overlap should demonstrate an exacerbated negative relation between poor math performance and math anxiety. Taking this view further, we would expect that for individuals with relatively low self-math overlap, the possibility of math failure should be minimally threatening to one's sense of self. Because these individuals' math ability is not meaningfully contributing to their self-integrity, math performance outcomes are less important to them and math should be a much less worry-inducing task. This in turn would potentially diminish the negative loop between poor math performance and math anxiety. In other words, individuals who integrate math into the self less (i.e., have lower self-math overlap) should demonstrate a decoupled relation between math anxiety and math performance (i.e., a reduced or even eliminated negative relation).

An alternative perspective is that the threat of math failure may promote a defensive response among those higher in self-math overlap, such that they employ protective cognitive biases to ameliorate the perceived threat (Gilbert et al., 1998; Sherman and Cohen, 2006). Individuals are motivated to arrive at conclusions which place the self in a favorable light (Kunda, 1987, 1990; Taylor and Brown, 1988). When individuals are motivated to maintain high levels of self-regard in a particular domain or area (e.g., math), one way that they may do so is through self-serving biases (Dunning et al., 1995). Thus, to reduce the threat of math failure (and the ensuing damage this might do to their perception of self), people higher in self-math overlap might overestimate how good they are at math, such that there is discordance between their perceived and objective math ability. Such overly positive expectations of their math performance could serve to insulate these individuals from the deleterious effects of ruminating about potentially poor math performance (Hopko et al., 1998; Pekrun, 2006; Ashcraft and Krause, 2007; Beilock and Gray, 2007). From this perspective, math failure should not be as threatening to self-integrity among those with lower self-math overlap and so would not be expected to promote a defensive response in them. Thus, these self-serving biases might be absent for individuals with lower self-math overlap, and their more precise perceptions of their math abilities (and any potential deficiencies therein) would in turn predict a stronger negative relation between math anxiety and math performance for those on the lower end of the self-math overlap spectrum compared to those on the higher end. In sum, this second hypothesis predicts that the more that math is integrated into the self (i.e., the higher one's self-math overlap), the more we should see a decoupling of the negative relation between math anxiety and math performance, a decoupling which may be explained – at least in part – by increased self-serving biases.

[2]Throughout the manuscript, we refer to the 'threat that poor math performance poses to one's sense of self-integrity (to the extent that math is important to one's sense of self, as measured here by self-math overlap)' more parsimoniously as 'threat of poor math performance,' 'threat of math failure,' 'threat to self-integrity,' or 'threat to the self.' Note, however, that this is not meant to imply an experimental manipulation of threat.

To summarize, in the present study we examined whether self-math overlap relates to math anxiety and the extent to which individuals value math. Furthermore, we tested two competing hypotheses (outlined above) regarding whether one's degree of self-math overlap moderates the relation between math performance and math anxiety. We also assessed the extent to which math self-serving bias may or may not explain (i.e., mediate) the potential moderating effect of self-math overlap.

MATERIALS AND METHODS

Participants

First-year University of Western Ontario undergraduate students were recruited as part of a larger study examining academic decisions in undergraduates. Participants were recruited through flyers which were placed on public bulletin boards randomly throughout campus and through online advertisements on Facebook and other social networking groups for first-year University of Western Ontario students. Recruitment materials made no mention of mathematics. From an initial sample of 186, two participants were excluded because they were not actually first year students and three participants were excluded for failing to meet *a priori* exclusion criteria (i.e., incorrectly answering more than one third of instructional manipulation check items; Oppenheimer et al., 2009), resulting in a total of 181 participants (66 males, 115 females, aged 17–20, $M = 18.55$, $SD = 0.39$).

Procedure

Data reported here are part of a larger dataset focusing on first-year undergraduates. All present measures were obtained in a single 2 h session in which participants completed a series of cognitive tasks and self-report measures. The order of the tasks was counterbalanced across participants, and the order of the questionnaires within the survey battery was randomized across participants. All cognitive tasks were presented using EPrime 2.0 and all surveys were presented through Qualtrics (Provo, UT, USA). Participants were seated at identical Dell desktop machines running Windows 8.1 roughly 60–70 cm from the screen (flat-screen LCD monitor). Participants completed the math and verbal task via keyboard input and all surveys and other tasks via mouse input. The session took approximately 2 h to complete, and all participants were compensated $20 CAD. All participants provided written consent and all procedures were approved by the University of Western Ontario Ethics Review Board.

Materials

All summary statistics of survey and behavioral measures are presented in **Table 1**.

Math Anxiety

Participants completed the short math-anxiety rating scale (sMARS; Alexander and Martray, 1989), in which they rated how anxious they feel in 25 math-related situations, such as "receiving a math textbook" and "walking to math class." Items were scored on a 0–4 scale, with a higher value indicating higher anxiety, and

TABLE 1 | Descriptive statistics and correlation matrix of survey and behavioral measures.

	Measure	M (SD)	1	2	3	4	5	6	7	8	9	10	11	12
1	Self-math overlap	3.24 (1.63)												
2	Math anxiety	30.62 (20.65)	−0.61***											
3	Math performance	50.64 (24.63)	0.35***	−0.36***										
4	Valuation of math	10.27 (5.04)	0.73***	−0.66***	0.32***									
5	Perceived math ability	1.89 (1.06)	0.70***	−0.71***	0.37***	0.75***								
6	Math bias	–	0.61***	−0.62***	–	0.68***	0.93***							
7	Trait anxiety	40.94 (10.73)	−0.21**	0.44***	0.02	−0.23**	−0.30***	−0.33***						
8	Working memory capacity	40.06 (15.57)	0.03	−0.06	0.13†	0.02	−0.02	−0.08	−0.08					
9	Self-literature overlap	2.91 (1.52)	−0.23*	0.18*	−0.17*	−0.18*	−0.15*	−0.10	0.07	0.12				
10	Self-friend overlap	4.79 (1.35)	−0.03	0.17*	0.00	−0.11	−0.11	−0.11	0.01	−0.01	0.07			
11	Verbal performance	−0.01 (0.75)	0.06	−0.22**	0.13†	0.15*	0.19*	0.15*	−0.07	0.15*	0.23**	−0.07		
12	Perceived reading ability	2.24 (0.93)	−0.06	−0.13†	−0.16*	−0.03	0.02	0.08	−0.23**	0.17*	0.46***	−0.08	0.37***	
13	Literature bias	–	−0.09	−0.05	−0.23**	−0.09	−0.06	0.03	−0.22**	0.12†	0.40***	−0.06	–	0.93***

*Covariates are shown in grey. N = 181. †p < 0.10, *p < 0.05, **p < 0.01, ***p < 0.001. M(SD) for bias measures are by definition 0(1) – see Methods for details. Note also that bias scores are residualized against math and verbal performance, respectively, so means for bias scores and correlations between a bias and a performance score are necessarily 0.*

summed for a composite measure of 0–100, with a higher value indicating higher math anxiety (Cronbach's $\alpha = 0.96$).

Self-Math Overlap

Participants completed a modified version of the Aron et al. (1992) IOS scale. Participants saw a series of seven Venn-diagrams with varying degrees of overlap, ranging from no overlap to almost complete overlap, and were instructed to indicate "how much your sense of yourself overlaps with the [specified] person or concept" (see **Figure 1**). To assess the unique contribution of including math in the self, relative to having a more complex self-concept, participants completed the IOS regarding their relationship with math as well as with their best friend and with literature. This resulted in three unique measures: self-math overlap, self-friend overlap, and self-literature overlap. Items were scored on a 0–6 scale, with a higher value indicating higher overlap.

Valuation of Math

Participants reported the extent to which they agreed with a number of statements regarding their views on mathematics. Statements were derived from the two motivation measures included in PISA 2012 (OECD, 2012): the intrinsic motivation to learn mathematics scale (INTMAT) and the instrumental motivation to learn mathematics scale (INSTMOT), a measure of extrinsic motivation. Two items were excluded from the INSTMOT scale to reduce the length of the survey. Example items include, "I look forward to my mathematics" (INTMAT), "I am interested in the things I learn in mathematics" (INTMAT), and "Mathematics is an important subject for me because I need it for what I want to study later on" (INSTMOT). The six items were scored on a 0–3 scale, with higher scores indicating greater agreement. Scores from the two scales were analyzed independently and were also summed to compute a composite measure of valuation of math (range: 0–18, with higher scores indicating greater valuation of math; Cronbach's $\alpha = 0.91$).

Trait Anxiety

Participants completed the 20-item trait anxiety inventory (TAI; Spielberger et al., 1970), which assesses how frequently participants experience generalized feelings of anxiety and calmness. The TAI was included to partial out any variance in math anxiety that is not specific to anxiety about math but rather is driven by overall anxiety. Items were scored on a 1–4 scale, with a higher value indicating higher anxiety, and were reverse coded where appropriate. Scores were summed for a composite measure of 20–80, with a higher value indicating higher trait anxiety (Cronbach's $\alpha = 0.93$).

Math Performance

Participants completed mental arithmetic problems and reported solutions in a free-response manner. Task trials were designed to be challenging and were adapted from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976; see also Lyons and Beilock, 2011). Trials were of four different operation types (addition, subtraction, multiplication, and division), and operations were presented in separate blocks, which were randomized across participants. (Examples problems: *Addition:* $49 + 27 + 36$, $66 + 89 + 32$; *Subtraction:* $551 - 268$, $461 - 157$; *Multiplication:* 71×9, 97×4; *Division:* $711 \div 3$, $568 \div 8$; note that all problems were presented vertically.) Each block lasted approximately 3 min, or until the participant completed their last trial if they were mid-trial when the 3 min elapsed. Importantly, participants were unaware of this time limit, thus alleviating the task of overt time-pressure. Math performance was measured as the total number of correctly solved problems within 3 min and was summed across all four blocks (higher score corresponds to higher math ability).

Verbal Performance

Participants completed a synonym matching task in which they were presented with a target word and proceeded to determine which of five words was most synonymous with the target word. Responses were made in a multiple-choice format. (Example items: *Target word:* Replete; *Potential synonyms:* Full, Elderly, Resentful, Discredited, Restful.) Trials were adapted from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976) and were designed to be somewhat challenging. Each trial lasted a maximum of 15 s. Participants completed one block of five practice trials, followed by two blocks of 18 trials each, summing to a total task time of about 5–6 min. Performance is measured via a combination of response-times and error-rates (z-scores for each measure were computed and averaged). Verbal performance was included to compute individuals' potential self-serving biases with respect to performance in a domain outside of math. As noted above, inclusion of such control measures allows us to ascertain the extent to which any bias effects observed are specific to math.

Perceived Math Ability and Math Bias

Participants reported their perceived math ability by responding to the single item, "I am just not good at math," adapted from the PISA index of mathematics self-concept (SCMAT; OECD, 2012). The item was reverse coded and scored on a 0–3 scale, such that higher scores indicate greater perceived ability. Previous work has demonstrated that perceived math ability is an important predictor of math anxiety (Ahmed et al., 2012) and is a path through which math anxiety exerts an effect on math performance (Meece et al., 1990). Here, we used this measure to compute individuals' potential self-serving biases with respect to math performance.

To compute a measure of self-serving math bias, we entered math performance (as measured by scores on the mental arithmetic task) as a predictor into a linear regression model predicting perceived math ability. We reasoned that any variance in perceived math ability that cannot be attributed to differences in individuals' math performance (a measure of their objective math ability) – i.e., perceived math ability residualized via the removal of the influence of actual math ability – would reflect a bias in one's assessment of one's math ability. Put another way, our math bias score is equivalent to perceptions of math ability that are independent of (i.e., orthogonalized with respect to) objective math performance. Positive bias scores thus indicate the presence of self-enhancing perceptions (i.e., an overestimation of one's ability, relative to the rest of the sample), whereas negative bias scores indicate self-deprecatory perceptions (i.e., an underestimation of one's ability, relative to the rest of the sample). Scores ranged from −2.44 to 1.64.

To assess biases specific to math rather than to general abilities, participants also completed an item assessing perceived literature ability, "I am just not good at reading," which was also reverse coded and scored on a 0–3 scale. To ensure that bias was specific to math, we computed a measure of literature bias in a similar fashion to use as a covariate in subsequent analyses (perceived literature bias ratings were orthogonalized with respect to verbal performance; range = −3.06 to 1.83).

Working Memory

As a measure of working memory capacity, participants completed the Automated Reading-Span (R-span) task (Conway et al., 2005; Unsworth et al., 2005). Working memory capacity was included to partial out variance in mental math ability attributable to more general cognitive factors. In each subtrial of the R-Span task, participants verified the semantic sensibility of a grammatically valid English sentence and were subsequently presented with a single letter. Performance on the verification task was maintained at ≥85% accuracy for all but two participants. (Because results did not differ whether we retained or excluded these participants, and because the working memory task is used only as a covariate of indirect interest, we retained these participants.) Each trial consisted of three to seven subtrials, at the end of which participants were asked to recall the letters in the same order that they saw them. If all letters were correctly recalled for that trial in the correct order, the score for that trial was the number of letters for that trial; if any recall errors were made, the score for that trial was zero. Total scores were summed across all trials (range: 0–75), with a higher value indicating higher working memory capacity. This measure was included to control for general cognitive capacity where math ability was a variable of interest.

RESULTS

All analyses were performed in R v. 3.1.2 and SPSS v. 22.

To test the specificity of effects to math anxiety, trait anxiety was included as a control variable in all analyses involving math anxiety. To assess associations specific to inclusion of math in self (rather than broad inclusion of other people or concepts in self), self-friend overlap and self-literature overlap were included as control measures in all analyses involving self-math overlap. To partial out variance in general cognitive capacity, working memory capacity was included as a control measure in all analyses involving math ability. To test that effects were specific to math ability and math bias, rather than general academic ability or bias, perceived literature ability and literature bias were included as control measures in all analyses involving perceived math ability and math bias, respectively. Because females tend to have higher levels of math anxiety (Hyde et al., 1990), gender was included as a covariate in all analyses involving math anxiety. Relations between variables are presented as r or partial-r values except in the case of moderation and mediation analyses, where unstandardized betas and standard errors are presented instead for ease of interpretation.

Validation of Self-Math Overlap

We predicted that identifying oneself strongly with math (i.e., having higher self-math overlap) would be associated with greater valuation of math. As expected, self-math overlap and valuation of math are highly positively correlated, $r_{179} = 0.731$, p = 2E-31. This association was unique to self-math overlap, as the partial correlation remained significant when controlling for self-friend overlap and self-literature overlap, partial-$r_{177} = 0.724$, p = 2E-30. Self-math overlap is also positively correlated independently with each of the two PISA scales (which we combined to compute a composite measure of valuation of math). Self-math overlap is associated with greater intrinsic interest in math, $r_{179} = 0.725$, p = 8E-31 (controlling for covariates, partial-$r_{177} = 0.715$, p = 3E-29), and with greater instrumental/extrinsic interest and motivation in math, $r_{179} = 0.516$, p = 1E-13 (controlling for covariates, partial-$r_{177} = 0.513$, p = 2E-13). A significant Steiger's t-test (Steiger, 1980) indicates that the association of self-math overlap with intrinsic interest in math is stronger than the association with instrumental/extrinsic interest, p = 3E-05 (controlling for covariates, p = 7E-05).

We also hypothesized that individuals who had higher self-math overlap would have lower math anxiety. Indeed, self-math overlap was inversely related to math anxiety, $r_{179} = -0.610$, p = 8E-20. This effect held even when controlling for self-friend overlap, self-literature overlap, trait anxiety, and gender, partial-$r_{175} = -0.567$, p = 2E-16.

Moderation Analyses: Self-Math Overlap, Math Performance, and Math Anxiety

Using correlational analyses, we next replicated the well-established negative relation between math performance and math anxiety, $r_{179} = -0.355$, p = 9E-07. This effect maintained even when controlling for trait anxiety, working memory capacity, and gender, partial-$r_{176} = -0.387$, p = 9E-08.

To assess whether self-math overlap might moderate the negative association between math performance and math anxiety, we entered self-math overlap, math performance, and their interaction term as simultaneous predictors of math anxiety in a linear regression model. If the association between math performance and math anxiety depends on an individual's self-math overlap, then we should see a statistically significant interaction term between self-math overlap and math performance. This is indeed what we observed: self-math overlap significantly moderated the association between math performance and math anxiety, $B = 0.099$, $SE = 0.029$, $t(177) = 3.443$, $p = 0.001$, 95% CI_B = [0.042, 0.156], such that the association between math performance and math anxiety weakened with higher levels of self-math overlap. This moderation held even when controlling for self-friend overlap, self-literature overlap, trait anxiety, working memory capacity, and gender, $B = 0.092$, $SE = 0.026$, $t(172) = 3.552$, p = 5E-04, 95% CI_B = [0.041, 0.144] (see **Table 2**). This effect cannot be attributed to differences in variability in math performance or math anxiety at different levels of self-math overlap, as the moderation is robust even in non-parametric analyses, $B = 0.158$, $SE = 0.080$, $t(177) = 1.978$, $p = 0.050$, 95% CI_B = [3E-04, 0.314] (controlling for all covariates, $B = 0.142$, $SE = 0.070$, $t(172) = 2.025$, $p = 0.044$, 95% CI_B = [0.004, 0.282]).

To decompose this interaction, we followed the recommendations of Aiken and West (1991) to examine simple slopes of the association between math performance and math anxiety among individuals higher (+1 *SD* above the mean of self-math overlap) and lower (−1 *SD* below the mean of self-math overlap) in self-math overlap. Among individuals with lower self-math overlap, there was a negative association between math performance and math anxiety, $B = -0.309$, $SE = 0.071$, $t(177) = -4.351$, p = 2E-05, 95% CI_B = [−0.450, −0.169] (controlling for self-friend overlap, self-literature overlap, trait anxiety, working memory capacity, and gender, $B = -0.319$, $SE = 0.063$, $t(172) = -5.060$, p = 1E-06, 95% CI_B = [−0.444, −0.195]), such that poorer math performance was associated with greater math anxiety. By contrast, among individuals with higher self-math overlap, there was no association between math performance and math anxiety, $B = 0.014$, $SE = 0.067$, $t(177) = 0.212$, $p = 0.832$, 95% CI_B = [−0.118, 0.146] (controlling for covariates, $B = -0.018$, $SE = 0.061$, $t(172) = -0.298$, $p = 0.766$, 95% CI_B = [−0.139, 0.103]) (see **Figure 2**). In sum, these results clearly indicate a moderating role for self-math overlap. With increasing levels of self-math overlap, the strength of the negative relation between math performance and math anxiety diminishes until there is essentially no significant relation between math performance and math anxiety among individuals who identify most highly with math (that is, include math in one's self). This amelioration of the negative association between math performance and math anxiety suggests that self-math overlap may protect individuals from the threat of poor math performance, rather than exacerbating the threat. Because results favor an insulating role of higher levels of self-math overlap, we next tested the proposed mechanism for this effect – namely, that individuals with higher self-math overlap would respond defensively to the threat of poor math performance (i.e., would maintain self-enhancing biases regarding their math ability).

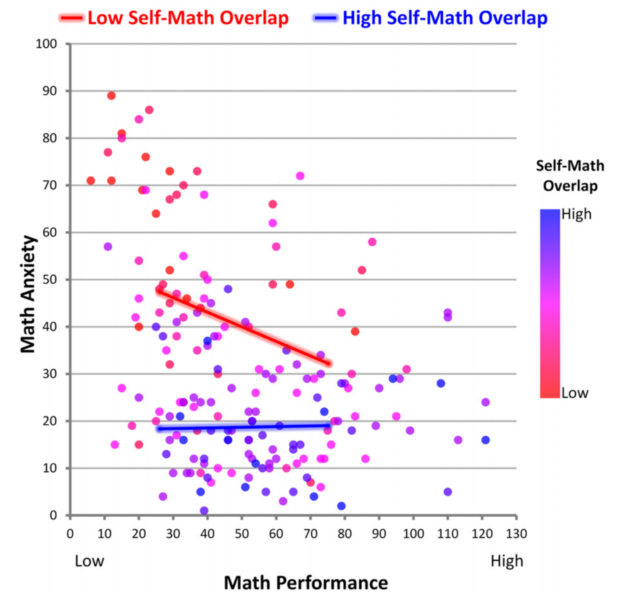

FIGURE 2 | Self-math overlap moderates the association between math performance and math anxiety. Among individuals higher in self-math overlap, the negative association between math performance and math anxiety is ameliorated. Data points are color coded by their level of self-math overlap, where blue indicates high overlap and red indicates low overlap. Note that although redder points (lower self-math overlap) exhibit a negative association between math anxiety (*y*-axis) and math performance (*x*-axis), bluer points (higher self-math overlap) exhibit no association. This can also be seen in the overlay figure, which is a line graph based on simple slopes of the data. Among individuals with lower self-math overlap (red line; −1 *SD* in self-math overlap), those exhibiting lower math performance exhibit higher levels of math anxiety than those exhibiting higher math performance, but among individuals with high self-math overlap (blue line; +1 *SD* in self-math overlap), there is no significant association between math performance and math anxiety. Lines are drawn from −1 SD to +1 SD in math performance.

TABLE 2 | Self-math overlap moderates the association between math performance and math anxiety.

	Math anxiety	
Variable	***B***	**95% *CI***
Math performance	−0.468**	[−0.659, −0.277]
Self-math overlap	−9.911**	[−12.649, −7.173]
Self-math overlap × Math performance	0.092**	[0.041, 0.144]
Self-friend overlap	2.204*	[0.518, 3.552]
Self-literature overlap	−0.269	[−1.680, 1.142]
Trait anxiety	0.565**	[0.360, 0.771]
Working memory	−0.023	[−0.160, 0.114]
Gender	5.325*	[0.675, 9.976]
Constant	35.539**	[18.431, 52.648]
R^2	0.573	
F	28.87**	

*Covariates are shown in grey. Outcome: Math Anxiety. N = 181. CI, confidence interval. *p < 0.01, **p < 0.001.*

Mediation Analyses: Testing the Role of Self-Enhancing Perceptions of Math Ability

Given that we observed no relationship between math performance and math anxiety in individuals who are higher in self-math overlap, we next tested the extent to which individuals' perceptions of their math ability might explain this decoupling. We expected that individuals with higher self-math overlap would exhibit greater self-serving biases regarding their math ability. We expected that this would be particularly true among individuals with higher self-math overlap who experience threat of math failure (i.e., poor math performance).

As outlined in the Methods, we computed a measure of self-serving math bias by entering math performance (as measured by the mental arithmetic task) as a predictor into a linear regression model predicting perceived math ability. Math performance significantly predicted perceived math ability, $r_{179} = 0.373$,[3] $B = 0.016$, $SE = 0.003$, $t(179) = 5.379$, p = 2E-07, 95% $CI_B = [0.010, 0.022]$, but explained only a portion of the variance in perceived math ability, $R^2 = 0.139$. The residual variance (i.e., perceived math ability residualized via removal of the influence of actual math ability) serves as our measure of math bias.

Recall that we expected individuals with higher self-math overlap to exhibit greater self-serving biases. Self-math overlap was indeed positively correlated with math bias, $r_{179} = 0.610$, p = 8E-20. This effect held even after controlling for self-literature overlap, self-friend overlap, and literature bias, partial-$r_{175} = 0.586$, p = 1E-17. Note that we predicted that individuals with higher self-math overlap would be most likely to demonstrate such self-serving biases specifically in the presence of a threat to the self (i.e., poor math performance). To test this, we entered self-math overlap, math performance, and their interaction term as predictors in a linear regression model predicting math bias. As expected, math performance significantly moderated the association between self-math overlap and self-serving biases, $B = -0.004$, $SE = 0.001$, $t(177) = -2.678$, $p = 0.008$, 95% $CI_B = [-0.006, -0.001]$, such that the positive association between self-math overlap and math bias was strongest when math performance was poorest. This moderation held even when controlling for self-friend overlap, self-literature overlap, working memory capacity, and literature bias, $B = -0.004$, $SE = 0.001$, $t(173) = -2.481$, $p = 0.014$, 95% $CI_B = [-0.006, -7E\text{-}4]$ (see **Table 3**). Decomposing the interaction revealed that among individuals with poorer math performance (-1 *SD*), self-math overlap more strongly predicted math bias, $B = 0.497$, $SE = 0.045$, $t(177) = 10.987$, p = 1E-21, 95% $CI_B = [0.408, 0.586]$, than it did among individuals with better math performance (+1 *SD*), $B = 0.314$, $SE = 0.056$, $t(177) = 5.665$, p = 6E-08, 95% $CI_B = [0.205, 0.424]$. These effects held when controlling for self-friend overlap, self-literature overlap, working memory capacity, and literature bias. Among individuals with poorer math performance, self-math overlap more strongly predicted math bias, $B = 0.495$, $SE = 0.046$, $t(173) = 10.688$, p = 9E-21, 95% $CI_B = [0.403, 0.586]$, than it did among individuals with better math performance, $B = 0.322$, $SE = 0.056$, $t(173) = 5.704$, p = 5E-08, 95% $CI_B = [0.211, 0.434]$.

If individuals with higher self-math overlap respond defensively to threats to the self, then the decoupling of the relationship between math performance and math anxiety by self-math overlap should be explained by their self-serving biases. That is, the *moderating* effect of self-math overlap (**Table 2**) on the association between math performance and math anxiety should be *mediated* by self-serving (math) biases (i.e., mediated moderation, sometimes referred to as moderated mediation; see Hayes, 2013, pp. 357–381). In this model, the moderating (i.e., interaction) term "Math Performance × Self-Math Overlap" is in effect the predictor variable, math anxiety is the outcome variable, and math bias is the mediator (see **Figure 3**). In the preceding analyses, we demonstrated that self-math overlap and math performance interactively predict both (1) the mediator (math bias, via the *a*-path; see preceding paragraph and **Table 3**) and (2) the outcome variable (math anxiety, via the *c*-path; see preceding section and **Table 2**). Next, we assessed the association between the mediator (math bias) and the outcome variable (math anxiety; the *b*-path). Math bias was negatively associated with math anxiety, $r_{179} = -0.625$, p = 5E-21, even when controlling for trait anxiety, literature bias, and gender, $r_{176} = -0.587$, p = 7E-18. This provides circumstantial evidence for mediated moderation, such that the interaction of self-math

[3]Note that this correlation is typical of the association between self-assessments of cognitive abilities and objective measures of cognitive abilities, where the average such correlation was found to be $r = 0.33$ in a recent meta-analysis (Freund and Kasten, 2012).

TABLE 3 | Math ability moderates the association between self-math overlap and math bias.

	Math bias	
Variable	***B***	**95% *CI***
Math performance	0.003	[−0.008, 0.013]
Self-math overlap	0.586***	[0.440, 0.732]
Self-math overlap × Math performance	−0.004*	[−0.006, −7E-4]
Self-friend overlap	−0.068	[−0.150, 0.015]
Self-literature overlap	0.021	[−0.061, 0.103]
Working memory	−0.003	[−0.011, 0.004]
Literature bias	−0.039	[−0.163, 0.089]
Constant	−1.002*	[−1.775, −0.229]
R^2	0.459	
F	20.92***	

*Covariates are shown in grey. Outcome: math bias. N = 181. CI, confidence interval. *p < 0.05, ***p < 0.001.*

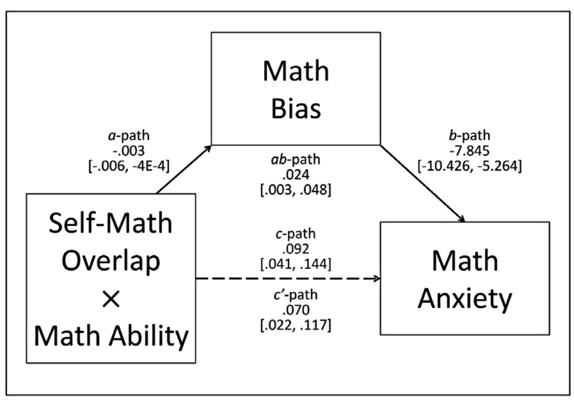

FIGURE 3 | Math bias was a significant partial-mediator of the interactive effect of self-math overlap and math ability on math anxiety, indicating that the relationship between the interaction of self-math overlap and math ability on math anxiety can be explained at least partially by levels of math bias. In particular, having higher self-math overlap and lower math ability is associated with lower math anxiety through higher self-serving math biases. Beta-coefficients and 95% confidence intervals from a model including self-literature overlap, self-friend overlap, trait anxiety, working memory capacity, literature bias, and gender as covariates are displayed. Note that when confidence intervals do not include zero, this indicates statistical significance.

overlap and math performance may exhibit a significant indirect effect on math anxiety through math bias. However, we need to directly test for the significance of the indirect effect (*ab*-path), and test what, if any, of the original (*c*) path remains after accounting for the mediator's contribution.

We did this using the PROCESS macro v. 2.13 in SPSS (Model 8)[4]. We tested this moderated mediation model using the bootstrapping method with 1,000 iterations (Preacher et al., 2007). As predicted, the confidence interval for the indirect (i.e., mediation) effect of the "self-math overlap × math performance" interaction via math bias on math anxiety (*ab*-path) did not cross zero, $B = 0.036$, $SE = 0.014$, 95% $CI_B = [0.011, 0.064]$, indicating statistically significant mediation. The original direct effect of self-math overlap × math performance on math anxiety (*c*-path) was therefore reduced by including math bias as a mediator to $B = 0.064$, $SE = 0.026$, $t(176) = 2.425$, $p = 0.016$, 95% $CI_B = [0.012, 0.115]$ (*c*'-path). Controlling for all covariates (self-literature overlap, self-friend overlap, trait anxiety, working memory capacity, literature bias, and gender), the *ab*-path remained significant, $B = 0.025$, $SE = 0.011$, 95% $CI_B = [0.003, 0.048]$, and the *c*-path remained reduced, $B = 0.070$, $SE = 0.024$, $t(170) = 2.907$, $p = 0.004$, 95% $CI_B = [0.022, 0.117]$ (*c*'-path; **Figure 3**). Importantly, note that the direct effect of self-math overlap × math performance on math anxiety remained statistically significant even when including math bias as a mediator, indicating only partial mediation. Thus, the decoupling observed between math performance and math anxiety as a function of self-math overlap can be explained only in part by individuals' biased perceptions of their math performance.

DISCUSSION

The present study indicates that the degree to which one incorporates math into one's self, self-math overlap, may be important for understanding math anxiety. We demonstrate that higher inclusion of math in the self is associated with higher levels of math valuation and lower levels of math anxiety. In doing so, this study is to our knowledge the first to directly link research on self-expansion and the inclusion of other in self to math anxiety. Given the simplicity and visual nature of this single-item measure, we believe it may hold great promise for understanding the cognitive, social, and emotional aspects of math and math anxiety, particularly in educational contexts. For example, here we show that self-math overlap may be important for decoupling the deleterious relationship between math performance and math anxiety. Among individuals with higher levels of self-math overlap, the typically observed negative relation between math ability and math anxiety is all but eliminated.

Notably, this result helps distinguish between two competing hypotheses regarding the interplay between cognitive and affective factors in math anxiety and math performance. From one perspective, highly valuing mathematics (i.e., so much so that math becomes integrated into one's sense of self) might make poor math performance a particularly worrying and anxiety-provoking experience. Valuing math (an affective factor) could compound an already recursive negative feedback cycle between poor math performance and math anxiety by exacerbating distractions and worries which tax additional cognitive resources. However, it instead appears that valuing mathematics so highly that one includes math in one's sense of self in fact shields the individual from maladaptive processes which can impair math performance and provoke anxiety. Our results also indicate a mechanism by which this decoupling occurs.

Specifically, it appears that self-math overlap may protect individuals from math anxiety – at least in part – through self-serving biases. A long line of research in social psychology demonstrates that individuals are motivated to hold the self in positive regard, and the present study rests on the well-established finding that individuals feel threatened when a valued part of their self is evaluated negatively (Greenwald, 1980; Steele, 1988, 1997). When one's ability to maintain positive self-perceptions is thwarted, individuals exhibit a number of defensive biases (Greenwald, 1980; Kunda, 1987, 1990; Dunning et al., 1995; Sherman and Cohen, 2002, 2006). Against this backdrop, our results indicate that individuals with higher self-math overlap appear to deal with the threat to self-integrity posed by the prospect of poor math performance by deluding themselves into believing their math performance is better than it actually is. In particular, we demonstrate that individuals higher in self-math overlap show relatively stronger self-enhancing biases in the math domain, and these biases explain – at least in part – the decoupling of the typically negative relation between math performance and math anxiety. Somewhat speculatively, the present study suggests that such biases may have protected these individuals from the pernicious and cognitively taxing loop between actual poor math performance and anxiety about poor math performance.

It is important to note that self-serving biases may not always be protective. Although self-serving biases are fundamental to mental health (Taylor and Brown, 1988), it is possible that such biases may lead to demotivation on future tasks (Kernis et al., 1988). To the extent to which individuals with strong self-enhancing biases about their math ability are demotivated to put forth the effort to study (perhaps believing that their effort is unnecessary for good performance given their perceived strong math abilities), self-enhancing biases may actually have the counterintuitive effect of eventually diminishing math performance. Although speculative, it is possible that individuals have higher self-math overlap simply because they recognize the societal importance of math (Parsons and Bynner, 2005; Nelson et al., 2008; Reyna et al., 2009, see also Pekrun, 2006), in which case *believing* that one is 'good' at math may be enough to satisfy external demands for strong math skills (c.f., Ryan and Deci, 2000) and may demotivate future effort. On the other hand, if individuals incorporate math into the self out of an inherent interest in or appreciation of math, self-enhancing biases likely increase their feelings of competence and facilitate their effortful engagement in mathematics (c.f., Ryan and Deci, 2000). Although it is likely a combination of extrinsic and intrinsic factors that lead

[4]PROCESS Model 8 was run using the following variable assignments: X = math performance, W = self-math overlap, M = math bias, Y = math anxiety. Covariates were applied in both the moderated and mediated components of the model.

individuals to incorporate math into their self, self-math overlap was more strongly related to intrinsic interest in mathematics than to instrumental interest in the present study. Thus, it seems more likely that self-enhancing biases about one's math abiltiy work more in a protective fashion, preserving intrinsic interest in math, and so perhaps encouraging future interest and engagement in mathematics.

Yet, although math self-serving biases explain a decoupled relation between math performance and math anxiety as a function of self-math overlap, it is important to note that math self-serving bias only partially mediated this effect. In other words, self-serving biases explain only a portion of the variance in math anxiety as a function of self-math overlap and math performance. Therefore, additional processes to explain this relationship must be at play. This is significant because it suggests that the mechanism by which self-math overlap predicts a decoupling of math performance and math anxiety cannot merely be reduced to individuals' self-serving biases in their perceptions of their math ability, i.e., their 'math self-concept.' Previous work has demonstrated that greater perceptions of one's own math abilities are associated with lower math anxiety (Meece et al., 1990; Pajares and Miller, 1994; Ahmed et al., 2012). If our analysis had exhibited full mediation, one might conclude that our measure of self-math overlap was simply serving as a proxy for math self-concept, and did not contribute anything novel to our understanding of the psychosocial factors which relate to math anxiety. However, this was not the case, indicating that self-math overlap likely bestows additional protective advantages with respect to math anxiety. One potential protective mechanism by which self-math overlap decouples the negative rleation beween math performance and math aniety may be the extent to which those higher in self-math overlap exhibit intrinsically motivated regulatory strategies (e.g., better emotional regulation when doing math; c.f., Ryan and Deci, 2000). Future work might examine whether such regulatory strategies explain additional variance in the decoupling of the negative relation between math performance and math anxiety by self-math overlap.

It is also noteworthy that individuals with lower levels of self-math overlap continued to exhibit a strong negative relation between math performance and math anxiety in the present study. This is somewhat counterintuitive given that individuals lower in self-math overlap value math less than those who have higher self-math overlap. One might have predicted an ameliorated or decoupled relation between math performance and math anxiety at relatively low levels of self-math overlap because if individuals do not value math as part of their identity, they can hardly be expected to feel pressure to perform well in math or to be anxious about their performance. However, this is not what we observe in the present study. Rather, the finding that lower self-math overlap individuals have a *stronger* negative relation between math performance and math anxiety suggests that they are potentially even more susceptible to worried rumination or distraction that exacerbates the negative loop between math anxiety and math performance. In other words, this result undercuts the notion that those who 'care' less about math are not math anxious or are immune to the pernicious relation between math anxiety and math performance. Although our results show this can be partly attributed to less positively biased perceptions of math ability among those with lower self-math overlap, the mediation effect was only partial. In other words, other more extrinsic factors (e.g., awareness of the importance of math skills for socially desirable outcomes) might be at work in these individuals.

On a methodological note, when discussing a decoupling of a negative relation between math performance and math anxiety through self-enhancing biased assessments of one's math performance, it is worth considering how these constructs are measured and the assumptions therein. Here, we measured performance via a difficult mental arithmetic task. However, more advanced mathematics such as algebra, geometry, calculus, etc., may – at least in the minds of the students assessed here – have relatively little to do with arithmetic skill. Though math tends to be a cumulative discipline, and considerable research has linked basic arithmetic and numerical skills with more advanced math abilities (e.g., Blaylock and Kopf, 2012; Lourenco et al., 2012; Price et al., 2013), individuals' *perceptions* of their math ability may not be so closely related to their arithmetic and numerical skills, especially if they have extensive training in advanced mathematics. Thus, the way in which math performance and perceptions of math ability are operationalized requires particular consideration, especially when studying those who are especially advanced in mathematics relative to more typical populations. Future work might consider whether self-math overlap exerts a uniform effect on the relation between math performance and math anxiety across more advanced mathematical contexts

Additionally, our measure of perceived math ability (from which we computed a measure of self-enhancing math bias) was a single item measure, and thus may potentially elicit objections that it fails to capture nuances in individuals' assessments of their math abilities. However, the correlation between perceived and actual math ability in the present study ($r = 0.37$), was in fact slightly *above* the overall average of such correlations ($r = 0.33$) observed across cognitive domains in the recent meta-analysis by Freund and Kasten (2012). Moreover, looking just at the relation between perceived and actual performance in the numerical domain with multi-item measures of perceived ability, the typical correlation was 0.40, which is only slightly higher than the relation observed here. Thus, although future work will no doubt further elucidate the nuanced relation between perceived and actual math ability, our measurement of these variables here does not seem to have unduly compromised our results.

On a practical note, our measure of self-math overlap is both brief and, given its visual nature (**Figure 1**), quite easy to understand. Many previous measures that examine a potentially related construct, math identification, have relied heavily upon positive perceptions of math abilities. Although we have shown that self-math overlap is positively related to perceived math ability, it is far from a one-to-one correlation. In fact, one of our critical results is that math self-serving bias only partially mediates the interactive effect of self-math overlap and math performance on math anxiety. This suggests that when it comes to math anxiety (and in particular the relation between math anxiety and math performance), self-math overlap appears to bring additional explanatory power. Moreover, the simplicity of this measure may also be well-suited to testing in a range of environments and populations, including cross-cultural and developmental contexts. Such work is particularly important given that the sample for the present study was comprised of 'WEIRD' undergraduate subjects (that is, subjects from Western, educated, industrialized, rich, and democratic backgrounds; Sears, 1986; Henrich et al., 2010) and may not generalize to other populations. Finally, as the results here suggest, self-math overlap may also prove useful for reducing the pernicious relation between math performance and math anxiety, and vice versa. To the extent that it is possible to explicitly intervene in ways that increase incorporation of math into one's sense of self, for example, such interventions may help reduce, delay, or even prevent some of the deleterious effects of math anxiety on math education.

In sum, the current work demonstrates that including math in one's sense of self – self-math overlap – predicts reduced math anxiety and a decoupling of the association between math ability and math anxiety. Individuals with higher self-math overlap exhibit biased perceptions of their own math ability, especially to the extent that they suffer from threat of poor math performance. These biases in turn partially explain the decoupling of the link between math performance and math anxiety in these individuals, though unique variance remained attributed to self-math overlap, suggesting a still deeper connection between this novel construct and math anxiety that warrants further investigation. Moreover, even though those lower in self-math overlap tended to value math less, we nevertheless observed a stronger negative relation between math anxiety and math performance in these individuals. This work thus presents a promising avenue for understanding the nuanced relation between math ability and math anxiety, and it provides a clear theoretical link between ongoing research in math anxiety and social psychological research on the benefits of including others in one's sense of self. Studying the strategies that individuals with high self-math overlap utilize in anticipation and performance of mathematics may inform methods for effectively intervening and disrupting the downward spiral between poor math performance and math anxiety.

ACKNOWLEDGMENTS

This work was supported by the Natural Sciences and Engineering Research Council (NSERC), Banting Postdoctoral Fellowships, and internal award from the University of Western Ontario (Research Western and Faculty of Social Science) to IML. We would like to thank Mark Ashcraft, Alysson Light, and Adrian Ward for their helpful comments and Ahmad Mousa for data collection and manuscript comments.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 19 April 2016
doi: 10.3389/fpsyg.2016.00513

Affective and Motivational Factors Mediate the Relation between Math Skills and Use of Math in Everyday Life

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This study focused on the use of math in everyday life (the propensity to recognize and solve quantitative issues in real life situations). Data from a Dutch nation-wide research on math among adults ($N = 521$) were used to investigate the question whether math anxiety and perceived math competence mediated the relationship between math skills and use of math in everyday life, taken gender differences into account. Results showed that women reported higher math anxiety, lower perceived math competence, and lower use of math in everyday life, compared to men. Women's skills were estimated at a lower level than men's. For both women and men, higher skills were associated with higher perceived math competence, which in turn was associated with more use of math in everyday life. Only for women, math anxiety also mediated the relation between math skills and use of math in everyday life.

Keywords: gender, math performance, math anxiety, perceived math competence, numeracy

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *07 July 2015*
Accepted: *29 March 2016*
Published: *19 April 2016*

Citation:
Jansen BRJ, Schmitz EA and van der Maas HLJ (2016) Affective and Motivational Factors Mediate the Relation between Math Skills and Use of Math in Everyday Life. Front. Psychol. 7:513. doi: 10.3389/fpsyg.2016.00513

INTRODUCTION

Math skills are important for functioning in everyday life as well as in various professions. Everyday life is full of challenges that demand math-related activities. Keeping a budget for example concerns most adults, both at large scale (e.g., in a household) and small scale (e.g., when shopping). It requires an overview and weighing of financial incomes and costs. Another example is planning, crucial for both adolescents and adults, demanding the reading of time tables or the assessment of activities' lengths in order to arrive or finish in time. As a final example, many individuals deal with the estimation of quantities when cooking or decorating their house. These situations are just a few examples but demonstrate the importance of using number knowledge, mathematical operations, and knowledge of math-related concepts like time. Nowadays, technology more and more provides devices to face these challenges, which often remove the need for mental calculations. However, also when using technological devices, mental calculations and estimations are crucial for a hunch of the outcome of for example a route planner or to check whether a discount is really beneficial. Reyna and Brainerd (2007) emphasize the relevance of mathematics skills for making decisions in everyday life, and note that a large number of adults in the USA do not possess the math skills "to handle the quantitative tasks of everyday life" (Reyna and Brainerd, 2007, p. 156). They also acknowledge that skills only do not suffice to handle these tasks. Here, we use data from a nation-wide research on math in the Netherlands, which offer the opportunity to investigate whether both math skills and emotional and motivational factors (math anxiety and perceived competence) are related to the use of mathematics in everyday life. Use of math in everyday life is defined as the propensity to recognize and solve quantitative issues in real life situations.

One affective factor that might play a role in the relationship between math skills and use of math in everyday life is math anxiety. Math anxiety can be conceived of as a performance-based anxiety, sharing important symptoms with other performance-based anxieties, such as social anxiety (Hopko et al., 2002; Ashcraft et al., 2007), which are experienced in situations that demand performance or when anticipating performance (see also Lyons and Beilock, 2012). Math anxiety refers to the persistent feelings of tension, apprehension and excessive fear in situations that require solving math problems in both ordinary life and academic situations (Beilock and Ramirez, 2011; Wu et al., 2014). Math anxiety has been shown to have a mutual negative relationship with math performance, often expressed in a correlation of around −0.3 (e.g., Hembree, 1990; Ma, 1999). Low math performance may cause the development of math anxiety (e.g., Hopko et al., 2002). The other way around, math anxiety may cause low math performance when, for example, anxiety-characteristic worries and arousal decrease performance (e.g., Ashcraft and Krause, 2007; Ashcraft and Moore, 2009). An alternative way in which math anxiety may cause low math performance is when avoidance inhibits the exercise of skills. Avoidance of math occurs when students rush through math work or exams, postpone math homework, drop math-related courses in high school, use heuristics instead of cognitive reflection, and limit use of math in everyday life (Hembree, 1990; Ashcraft, 2002; Morsanyi et al., 2014). The present study sets out to study this association, between the degree of math anxiety and the avoidance of math in everyday life.

Additionally, gender differences are of specific relevance, as numerous studies show that women report higher levels of math anxiety than men (Hembree, 1990; Meece et al., 1990; Miller and Bichsel, 2004; Bonnot and Croizet, 2007; Marsh et al., 2008; Devine et al., 2012), although other studies show only small gender differences (Chinn, 2009) or no gender differences at all (Chiu and Henry, 1990; Ma, 1999; Ho et al., 2000; Ma and Xu, 2004; Birgin et al., 2010; Erturan and Jansen, 2015). A gender difference in math anxiety may relate to the lower female participation in professions in science, technology, engineering and mathematics (STEM; Bureau of Labor Statistics, US Department of Labor, 2014; www.cbs.nl). Both females' elevated level of report of math anxiety and their lagging representation in technical professions cannot easily be explained by skill differences. Gender differences in mathematics performance fluctuate with the measurements used and the country under study (Else-Quest et al., 2010), but range from girls outperforming boys in math grades (Pomerantz et al., 2002), to no gender differences (Miller and Bichsel, 2004; Devine et al., 2012) and small male advantages (Liu and Wilson, 2009).

An important factor in the realization of gender differences in math anxiety seems to be whether the assessment concerns state or trait math anxiety. Trait anxiety concerns individuals' beliefs on their anxiety, whereas state anxiety concerns momentary emotions (Robinson and Clore, 2002). Goetz et al. (2013) assessed both state and trait math anxiety and showed that individuals' reports on trait math anxiety were often higher than those on state math anxiety. In the present study, we assess individuals' trait math anxiety, which has been shown to relate to math performance (e.g., Hembree, 1990), and avoidance of math-related activities (Chinn, 2009).

Our first research question concerns the association between math anxiety and the use of math in everyday life, taking math skills and gender differences into account. We hypothesize that there is a positive relation between math skills and use of math in everyday life that is however mediated by math anxiety, in the sense that higher skills are negatively related to math anxiety, which is again negatively related to use of math in everyday life. The relations between math skills, use of math in everyday life and math anxiety are investigated for women and men separately because the relationship between math skills and math anxiety is expected to be stronger for women than for men (Devine et al., 2012; Erturan and Jansen, 2015; but see Hembree, 1990; Meece et al., 1990; Ma and Xu, 2004; Miller and Bichsel, 2004).

A second factor that might play a role in the relationship between math skills and the actual use of math in daily life is an individuals' perceived competence of performing math. Various concepts of self-beliefs exist and definitions sometimes overlap. Central in concepts like self-efficacy and perceived competence is a person's perception of his/her competence, sometimes in relation to peers (Harter, 1982; Jansen et al., 2013). Self-beliefs about math are related to career interest in math and science (O'Brien et al., 1999) as well as to mathematics anxiety (Meece et al., 1990). Control-value theory (Pekrun, 2006) states a negative causal relation between perceived control of success and anxiety. Anxiety may result from both the expectation of being unsuccessful in a given situation and the valuing of success in the situation. Indeed, this relationship is supported empirically for the domain of math (Bieg et al., 2013). The mutual relation between self-belief and mathematics performance is established as well (Marsh et al., 2005; Liu, 2009; Erturan and Jansen, 2015). Here, we focus on perceived math competence: A person's feeling of being competent to successfully accomplish math tasks. A high confidence in one's math competence may ease the use of mathematics in everyday life. Reports of females' lower self-beliefs concerning math, compared to males', are more numerous (Meece et al., 1990; Pomerantz et al., 2002; Else-Quest et al., 2010; Goetz et al., 2013) although reports of similar levels of perceived math competence have been reported as well (Jansen et al., 2013; Erturan and Jansen, 2015).

Our second research question centers on the role of perceived math competence in the use of math in everyday life, next to math anxiety, and taking into account math skills and gender differences. We hypothesize that the relation between math skills and use of math in everyday life is also mediated by perceived math competence, in the sense that math skills are positively related to perceived math competence, which is again positively related to use of math in everyday life. The possible mediating effects of math anxiety and perceived math competence are included simultaneously, in one model. The present data allow for investigating whether math performance has an impact on math anxiety through perceived math competence, as might be derived from control-value theory (Pekrun, 2006). However, our interest is on the relation between perceived math competence and use of math in everyday life, a concept which is only scarcely studied, taking into account relations between math anxiety, perceived math competence, and math performance. Again, the relation is investigated separately for men and women.

The Present Study

The present study is conducted as part of a nation-wide research on math in the Netherlands. A large scale data collection was conducted concerning different facets of mathematics, for various studies on mathematics of different researchers. For the present study, data on emotional and motivational factors as well as the use of math in everyday life and math skills have been investigated. Data collection was online, which allowed participants to fill in the tests and questionnaires in their own time, in a familiar environment. The collected data offer the opportunity to investigate our research question, that is, whether math anxiety and perceived math competence mediate the relationship between math skills and use of mathematics in everyday life. Regarding gender differences, we hypothesize that (1a) women report higher levels of mathematics anxiety than men; (1b) women's math skills are equal to those of men; (1c) women report lower levels of perceived math competence than men. Regarding the relation between math skills, use of math in everyday life, math anxiety, and perceived math competence, we hypothesize that (2a) the relation between math skills and use of math in everyday life is positive but (2b) is mediated by math anxiety, in the sense that math skills are negatively related to math anxiety, which is negatively related to use of math in everyday life. Finally, we hypothesize that (2c) the relation between math skills and use of math in everyday life is also mediated by perceived math competence, in the sense that math skills are positively related to perceived math competence, which is again positively related to the use of math in everyday life. The relation between math skills and use of math in everyday life, possibly mediated by math anxiety and perceived math competence, is investigated separately for men and women.

METHODS

Participants

The Grand National Research on Math is an initiative of the Netherlands Organization for Scientific Research (NWO), and two Dutch broadcasters. Participants responded to calls in a Dutch television program on popular science and on the Internet to fill out questionnaires on math and solve math problems on a central website of the Grand National Research. Different tasks and questionnaires were presented on the website. Participants were free to choose what they were interested to do on the website and thus which parts to complete. A total of 1066 individuals filled in the questionnaire on math in everyday life. From this sample, 556 participants also filled in the questionnaires on math anxiety and perceived math competence and finished at least one session of the addition game in Math Garden (see below). Data from 20 participants were excluded because they were younger than 18 years old. Additionally, data from 15 participants, who had followed primary school outside the Netherlands, were excluded. The final sample consisted of 521 participants (59% females). The average age of the participants was 45.72 years ($SD = 14.68$; range: 18.54–79.14 years).

The upper panel of **Table 1** shows the number of women and men, by level of highest completed education. The sample had a relatively high level of education, compared to the general population in the Netherlands. A chi-square test demonstrated that highest completed education and gender were not independent, $\chi^2_{(6)} = 19.76$, $p = 0.003$. Relatively more men than women had finished higher secondary education. However, this category contained only a minority of the participants (10%) and it is not very likely that the skewed distribution in this category would cause a gender difference in math skills in the present sample. The lower panel of **Table 1** shows the number of women and men by profession, in descending order of total frequency. Only the seven most frequently named professions are shown. Unemployed participants and students did not answer this question. Gender distribution differed across professions, $\chi^2_{(8)} = 72.64$, $p < 0.001$. Relatively more women worked in care and welfare, whereas relatively more men worked in ICT and construction and engineering professions, reflecting Dutch societal differences (www.cbs.nl).

TABLE 1 | Numbers of women and men in the current sample, by level of highest completed education and by profession.

	Females (% of females)	Males (% of males)	Total (% of total sample)
LEVEL OF HIGHEST COMPLETED EDUCATION			
PhD	12 (4%)	9 (4%)	21 (4%)
Master's degree	71 (23%)	48 (22%)	119 (23%)
Bachelor's degree	108 (35%)	63 (29%)	171 (33%)
Higher sec. educ.	16 (5%)	36 (17%)	52 (10%)
Vocational educ.	43 (14%)	23 (11%)	66 (13%)
Intermediate sec. educ. or lower	10 (3%)	6 (3%)	16 (3%)
No response	47 (15%)	29 (14%)	76 (15%)
PROFESSION			
Education	48 (16%)	20 (9%)	68 (13%)
Care and welfare	51 (17%)	14 (7%)	65 (13%)
ICT	8 (3%)	38 (18%)	46 (9%)
Trade and hospitality	8 (3%)	13 (6%)	21 (4%)
Science	14 (5%)	6 (3%)	20 (4%)
Economy and finance	6 (2%)	12 (6%)	18 (4%)
Construction and engineering	3 (1%)	14 (7%)	17 (3%)
Other	40 (13%)	16 (7%)	56 (11%)
Students	47 (15%)	29 (14%)	76 (15%)
No income from profession	82 (27%)	52 (24%)	134 (26%)
Total	307	214	521

Material

Math Anxiety

A measurement of math anxiety was obtained by administering the Dutch translation of the Math Anxiety Scale for Children (MASC; Chiu and Henry, 1990; Dutch translation was reported in Jansen et al., 2013). The overarching national research was set up to include both children and adults. Hence, a questionnaire was selected that could serve all age groups. The MASC could be administered to students, reporting their current math anxiety, and to adults, who were asked to report on their math anxiety in retrospect. A child questionnaire can be relevant for adults because many math-related experiences were at school, which is a period that most adults can vividly remember. Both positive and negative feelings around math often arise at school.

The MASC consisted of 23 statements, for example "Listening to the teacher in a math class" and "Waiting to get a math test returned in which you expect to do well." Participants rated their anxiety on a four-point scale, ranging from 1 ("not nervous") to 4 ("very nervous"). Scores ranged from 23 to 92, with a higher score indicating a higher level of (retrospective) math anxiety.

Perceived Math Competence

Perceived math competence was assessed using an adaptation of the scale Perceived Math Competence (Jansen et al., 2013), which was an extension of the Perceived Competence Scale for Children (Harter, 1982; Dutch translation by Veerman et al., 1997). Adaptation concerned the answer format of the scale. The scale consisted of six statements. Example statements were "It takes me long to solve math problems" and "I am struggling with math." Statements were relevant for both children and adults. Participants indicated the extent to which each statement applied to them, using a four-point scale, ranging from 1 ("does not apply to me at all") to 4 ("fully applies to me").

Math Skills

An approximation of math skills was obtained using a customized version of Math Garden. Math Garden is a computer-adaptive web-based practice and monitoring system for math (Klinkenberg et al., 2011). In this customized version, four math games were presented. Here, we focused on the addition game. Correlations between the addition game and the other games (mental arithmetic, series, 24-game) were high. A session of the addition game consisted of 15 sequentially presented addition problems, like $3 + 4, 234 + 48$, and $234.78 + 32.98$. Each addition problem was presented with six answer options, of which only one was correct and participants had 20 s to select the correct answer. A response was followed by highlighting the correct response alternative. Correct responses were rewarded, whereas errors were penalized. Penalty and reward of responses were linearly related to response time: Fast errors were more severely penalized than slow errors, whereas fast, correct responses were higher rewarded than slow correct responses (Maris and Van der Maas, 2012).

Selection of problems was adaptive, meaning that a more difficult problem was presented after a correct response and an easier problem after an error. Problem difficulties were extracted from Math Garden (Klinkenberg et al., 2011). Based on both response time and accuracy, each participant's ability was rated on a scale that ranged from approximately -10 to $+10$, although the end points were in principle infinite. A person's ability was adjusted upwards in case of a correct response and adjusted downwards in case of an incorrect response. Degree of adjustment depended on both speed and difficulty of the presented math problem (Klinkenberg et al., 2011).

Everyday Life

Table 2 shows the questionnaire that was developed for the present study to assess use of math in everyday life, i.e., the propensity to recognize and solve quantitative issues in real life situations. The questionnaire consisted of 18 situations of possible applications of math in everyday life and 2 questions on the number of math-related activities that were employed in free time or in performing a profession. Each of the 18 situations was presented in an unfinished sentence, together with multiple question-specific complements to choose from. An example of a situation was "When paying in a shop…," with complements "I do not check the amount of money returned," "I look at the cashier to know the amount to be returned," and "I know the exact amount to be returned" (see **Table 2** for statements; see Appendix in Supplementary Materials for complements). Participants selected the complement that applied most to them. Two points were assigned to a complement that was judged on forehand to be associated with performing math, without any aids; one point was assigned to a complement that was associated with estimation or using a tool or device; no points were assigned to remaining complements. The response "inapplicable" was recorded as missing. The two additional questions on engagement in math-related activities in free-time or in a profession had multiple options to choose from (see items 19 and 20 in **Table 2**). Participants could indicate their engagement in up to 2 math-related activities in free time (score: 0–2) and in up to 4 math-related job activities (score 0–4). The total score on the everyday life questionnaire could range from 0 to 42, with a higher score corresponding to increased math-related activities in everyday life.

Procedure

The Grand National Research on Math was performed under the responsibility of the Netherlands Organization for Scientific Research (NWO), and two Dutch broadcasters. The research was announced in a television show on popular science. Viewers were notified of the possibility to voluntarily participate in the online research. Visitors of the website were first explained the privacy policy of the research. Participants were informed that participation was anonymous, that results were not traceable to individuals and that data were used for scientific purposes only, respecting the Data Protection Act. Participants had the possibility to enter their e-mail address in case they would like to be informed of their personal scores, but e-mail addresses were not used in data processing. No personal information was used for scientific research. Participants had complete control of continuing or terminating their participation because the researcher was not present during the research and participants could leave the website whenever they wanted. Material did not

TABLE 2 | Questionnaire on use of math in everyday life.

Unfinished statement	Factor loadings				Mean score (SD) (range 0–2)
	1	2	3	4	
2. If there is a discount on a product	**0.46**	0.01	0.10	0.24	1.4 (0.50)
4. When paying in a shop	**0.50**	−0.15	0.21	**0.35**	1.6 (0.69)
7. When adding 68 and 178	**0.72**	0.25	−0.02	−0.06	1.9 (0.33)
8. When adding three monetary amounts	**0.79**	0.05	0.02	−0.07	1.7 (0.46)
9. If the clock is adjusted, I know if I have to get up sooner or later because	0.24	**0.55**	0.06	−0.03	1.5 (0.59)
10. I'll find out the number of days in each month	0.18	**0.65**	−0.21	0.01	1.5 (0.50)
12. If I'm in a different time zone and want to know the time in the country of departure	−0.04	**0.44**	0.28	0.04	1.7 (0.60)
17. I locate the south at daytime	−0.13	**0.63**	0.08	0.10	1.7 (0.69)
5. If I pay with paper money	0.27	−0.13	**0.43**	0.13	1.8 (0.58)
15. If I'm going to paint a wall	0.11	0.10	**0.61**	−0.04	1.5 (0.56)
16. If I cook soup for eight guests, but the recipe is for six	0.04	0.01	**0.71**	−0.22	1.6 (0.50)
1. When doing errands	0.18	−0.06	−0.14	**0.68**	0.8 (0.44)
6. When receiving the bill in a restaurant	−0.10	0.19	0.00	**0.70**	0.9 (0.56)
11. If I travel to a new destination by car and need to be there on time	–[1]	–[1]	–[1]	–[1]	0.8 (0.39)
13. If I travel to an unknown destination by bike or car I determine my route	–[1]	–[1]	–[1]	–[1]	0.9 (0.26)
14. If I travel to an unknown destination by public transport, I determine my route	–[1]	–[1]	–[1]	–[1]	1.0 (0.14)
20. In my spare time (multiple answers possible)	–[1]	–[1]	–[1]	–[1]	0.9 (0.75)
3. When I fill out my tax forms	–[2]	–[2]	–[2]	–[2]	1.4 (0.90)
19. For my profession (multiple answers possible)	–[2]	–[2]	–[2]	–[2]	1.3 (1.36)[3]

Items are arranged by factor. Factor loadings higher than 0.30 are printed in bold.
[1]Item was not included in Principal Component Analysis because of low inter-item correlations; [2]Item was not included in Principal Component Analysis because Cronbach's alpha decreased if item was deleted. [3]Scores can range from 0 to 4.

relate to medical issues, did not include a screening procedure and chance incidents were not possible. There was no deception. Discomfort due to participation was unexpected. For Math Garden, the Ethical Committee of the University of Amsterdam approved of the procedure of passive consent.

Upon their first visit of the website, participants received a personal identity number. Participants answered general questions on demographic information. Next, participants were free to participate in any of the studies on math. The present measures were reached by using three links: one for the questionnaires on math anxiety and perceived math competence, one for Math Garden, and one for the questionnaire on use of math in everyday life. Participants were free to choose order and timing of responding to the measures and any order was allowed. Data on the order of responding to the measures were not logged, making it impossible to test whether filling out one measure (e.g., the questionnaire on math anxiety and perceived math competence) has affected performance on a different measure (e.g., Math Garden).

RESULTS

Use of Math in Everyday Life Questionnaire: Reliability and Factor Structure

Reliability and factor structure of the questionnaire on math in everyday life were investigated first because the questionnaire was newly developed. Data from all 1066 participants who responded to the questionnaire were included. Items 11, 13, 14, and 20 were excluded from further analyses because scores on these items had low inter-item correlations (average correlation was below 0.05). Calculations of Cronbach's alpha if items were deleted pointed to the additional exclusion of items 3 and 19. Cronbach's alpha was $\alpha = 0.687$ for the remaining 14 items.

A Principal Component Analysis, using direct oblimin rotation, resulted in the extraction of four factors with an eigenvalue higher than 1. Together, the factors explained 45.8% of the variance. Loadings for the four factors are presented in **Table 2**. Items that referred to an interest in mental arithmetic loaded highest on the first factor, which was coined "Mental Arithmetic." The second factor seemed to concern knowledge of math-related facts like how to locate the south at day-time and was coined "Math-related Facts." Items on use of math in daily situations like converting the amount of ingredients of a recipe loaded highest on the third factor, which was coined "Practical Math." Items that referred to keeping a budget (doing errands, a restaurant bill) loaded high on the fourth factor, coined "Budget." Note that factors Mental arithmetic and Practical math fitted the definition of use of math in everyday life best. Internal consistency of an aggregate of the 8 items that loaded highest on these 2 factors (> 0.4) was $\alpha = 0.628$. Further analyses were performed with both the total sum scores of the 14 items (Total use everyday life) and the sum score on the 8 items that had high loadings on factors Mental Arithmetic and Practical Math ("Mental and practical math use").

Investigating Gender Differences in Math Anxiety, Perceived Math Competence, Use of Math in Daily Life, and Addition Skills

The hypotheses on (the absence of) gender differences in math anxiety, perceived math competence, and math skills were investigated next. We studied gender differences in the use of math in everyday life exploratory because no hypothesis was formulated for this domain. Mean scores by gender for math anxiety, perceived math competence, addition skill ratings and use of math in everyday life are presented in **Table 3**. A Multivariate Analysis of Variance (MANOVA) with math anxiety and perceived math competence, addition skill and use of math in daily life as dependent variables and gender as the independent variable showed a significant main effect of gender, $F_{(5, 515)} = 18.75$, $p < 0.001$, $\eta^2 = 0.154$. *Post-hoc* univariate tests showed that gender differences were observed for all variables. As expected, females reported higher levels of math anxiety and lower levels of perceived math competence than males. Females' estimated addition skills were lower than males', which was unexpected. Finally, females reported lower use of math in everyday life, compared to males.

Note that the effect size for the gender difference in addition skills was much lower than that for all other variables. Exploratory, we studied whether gender would explain additional variance in math anxiety and perceived math competence, when already taking into account addition skills. This was tested in a MANOVA with math anxiety and perceived math competence as dependent variables and gender, addition skills, and the interaction between gender and addition skills as independent variables. All main effects and the interaction effect were significant in the MANOVA.

The main effect of skill was significant, implying that for individuals with lower skills math anxiety was higher $F_{(1, 517)} = 42.02$, $p < 0.001$, $\eta^2 = 0.075$, and perceived math competence was lower, $F_{(1, 517)} = 62.66$, $p < 0.001$, $\eta^2 = 0.108$. The main effect of gender indicated higher math anxiety and lower perceived math competence scores for women compared to men (see **Table 3**). The interaction effect between gender and addition skills was significant for math anxiety, $F_{(1, 517)} = 24.75$, $p < 0.001$, $\eta^2 = 0.046$, and perceived math competence, $F_{(1, 517)} = 62.66$, $p < 0.001$, $\eta^2 = 0.108$. It was investigated by performing multigroup regression analyses with math anxiety/perceived math competence as the dependent variable, skills as the independent variable, and gender as group variable. As expected, given the interaction effect, estimating different values for the relation between skills and math anxiety for men and women improved the model significantly, $\chi^2_{(1)} = 28.95$, $p < 0.001$ for math anxiety; $\chi^2_{(1)} = 8.428$, $p = 0.004$ for perceived math competence. Concerning math anxiety, the relation with skills was not significant for men ($B = -0.522$, $p = 0.141$), but significant for women ($B = -3.965$, $p < 0.001$). Concerning perceived math competence, the relation with skills was weaker for men ($B = 0.642$, $p < 0.001$) than for women ($B = 1.311$, $p < 0.001$).

In sum, the results supported hypotheses 1a and 1c, that females were associated with higher math anxiety and lower perceived math competence than males. Hypothesis 1b, that gender differences would be absent in addition skills, was not supported as females' estimated addition skills were lower than males'. However, these gender differences in skills did not fully explain the gender differences in reported math anxiety and perceived math competence. Independent of skills, females reported higher math anxiety and lower perceived math competence.

TABLE 3 | Descriptive statistics for math anxiety, perceived math competence, ratings of addition skill, and use of math in everyday life.

	Mean (*SD*)		Univariate test	
	Females	Males	$F_{(1, 519)}$	η^2
Math anxiety	38.12 (14.55)	29.73 (7.67)	59.56*	0.103
Perceived math competence	17.41 (4.99)	21.04 (3.20)	87.91*	0.145
Ratings of addition skills	6.86 (1.46)	7.25 (1.47)	9.06*	0.017
Use of math in daily life: total	20.22 (3.78)	22.13 (2.85)	39.34*	0.070
Use of math in daily life: mental and practical math use	12.45 (2.54)	13.49 (1.97)	25.17*	0.046

*$p < 0.001$.

Mediation Effects of Affective and Motivational Factors in the Relation between Skills and Use of Math in Everyday Life

Next, it was investigated whether the relation between skills and use of math in everyday life was positive and mediated by both math anxiety and perceived math competence. Multigroup analyses were performed, with gender as group variable. First, a set of hierarchical regression analyses was conducted to investigate the predictive value of skills on use of math in everyday life (Step 1) and the possible added predictive value of math anxiety and perceived math competence (Step 2). In both step 1 and step 2, it was tested whether the estimates of the predictor(s) could be restricted to be equal across genders.

Table 4 summarizes the results of the hierarchical regression analysis, by gender. In step 1, the model improved significantly when estimating the relation between skills and use of math in everyday life for men and women separately, $\chi^2_{(1)} = 11.083$, $p = 0.001$, compared to a model in which this estimate was restricted to be equal across genders. Although positive for both, the relation was stronger for women than for men (see **Table 4**). In step 2, restricting the parameter estimating the predictive value of perceived math competence did not deteriorate the model significantly, $\chi^2_{(1)} = 2.127$, $p = 0.145$. Restricting the parameter estimating the predictive value of math anxiety however did deteriorate the model significantly, $\chi^2_{(1)} = 7.676$, $p = 0.006$. Hence, **Table 4** shows the estimates of the multigroup model with gender-specific relations between skills as well as math anxiety and use of math in everyday life, and a general relation between perceived math competence and use of math in everyday life. For men, only the positive relation between perceived competence and use of math in daily life was significant. For women, addition skills as well as math anxiety and perceived math competence significantly predicted use of math in everyday life, in the expected directions.

The same model selections were made when using scores on Mental and practical math use only (see **Table 4** for estimates): The relation between addition skills and use of math in everyday life was gender-specific, $\chi^2_{(1)} = 9.500$, $p = 0.002$, just like the relation between math anxiety and use of math in everyday life, $\chi^2_{(1)} = 10.802$, $p = 0.001$, but not the relation between perceived math competence and use of math in everyday life, $\chi^2_{(1)} = 3.591$, $p = 0.058$. For men, again only perceived math competence was related to use of math in everyday life. For women, there was again a significant negative relation between math anxiety and use of math in everyday life and a significant positive relation between perceived math competence and use of math in everyday life. The relation between addition skills and use of math in everyday life was not significant anymore.

Next, multigroup mediation analyses were performed. A model with all parameters restricted to be equal across genders deteriorated the model significantly, $\chi^2_{(5)} = 47.53$, $p < 0.001$, compared to a model where all parameters were estimated freely. The results of the hierarchical regression models suggested that the parameter that reflected the relation between perceived math competence and use of math in everyday life could be restricted to be equal across genders and this indeed did not deteriorate the model significantly, $\chi^2_{(1)} = 2.13$, $p = 0.094$. This multigroup mediation model is shown in **Figure 1**. For men only the indirect path through perceived math competence, and not math anxiety, had significant relations. The indirect effect of perceived math competence was indeed significant for men (bootstrapped confidence interval: 0.08–0.27; determined using scripts by Selig and Preacher, 2008), supporting the hypothesis that perceived math competence mediated the relationship between addition skills and use of math in everyday life for men. For women, indirect paths through both math anxiety and perceived math competence showed significant relations. Both indirect effects turned out to be significant for women (bootstrapped confidence interval for math anxiety: 0.14–0.45; bootstrapped confidence interval for perceived math competence: 0.08–0.26).

Using scores on Mental and practical use only, model selection deviated slightly, resulting in the selection of the saturated model, where all parameters were estimated freely for men and women. For men, again only the indirect effect of perceived math competence was significant and for women again the indirect effects of both perceived math competence and math anxiety were significant. Interpretations of indirect effects were highly similar to the interpretations of the model when using the total score on the questionnaire for use of math in everyday life.

In sum, results supported hypothesis 2a that math skills (estimated with an addition task) were positively related to the use of math in everyday life for both men and women. For men, the relation was indirect, through the level of perceived math competence: Higher addition skills were related to higher perceived math competence, which was related to a higher use

TABLE 4 | Hierarchical multigroup regression analyses predicting use of math in everyday life by addition skills, math anxiety and perceived math competence, with gender as group variable.

	B	SE B
MALES		
Step 1: model including total effect of addition skills		
Addition skills	0.271* (0.113)	0.131 (0.091)
Step 2: model including direct effect of addition skills		
Addition skills	0.107 (0.006)	0.126 (0.088)
Math anxiety	−0.009 (0.006)	0.026 (0.018)
Perceived math competence	0.248*** (0.172***)[a]	0.044 (0.031)
FEMALES		
Step 1: model including total effect of addition skills		
Addition skills	0.909*** (0.521***)	0.138 (0.095)
Step 2: model including direct effect of addition skills		
Addition skills	0.292* (0.115)	0.127 (0.089)
Math anxiety	−0.073*** (−0.045***)	0.017 (0.012)
Perceived math competence	0.248*** (0.172***)[a]	0.044 (0.031)

Estimates and statistics for model with Mental and practical math use as outcome variable in brackets.
[a]*Restricted to be equal across genders.* *$p < 0.05$; ***$p < 0.001$.

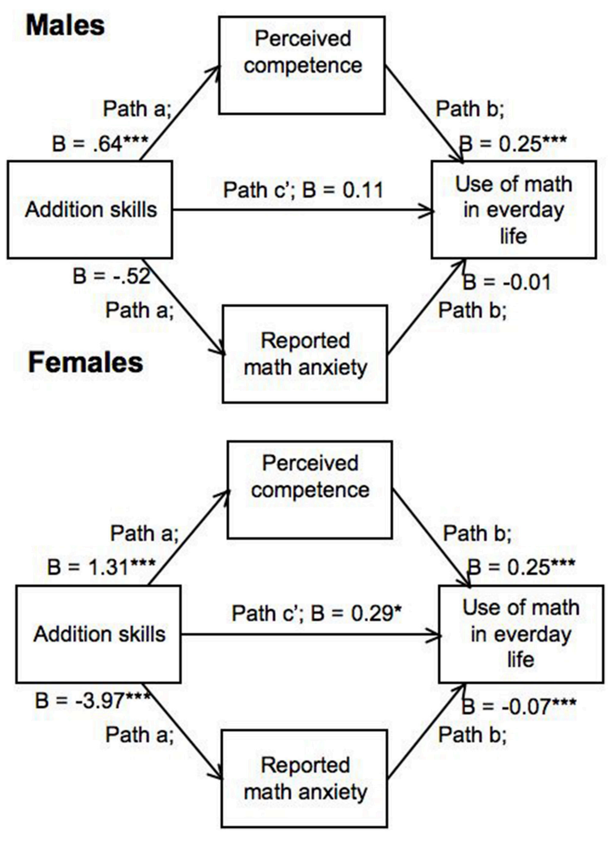

FIGURE 1 | Multigroup mediation model with relation between perceived math competence and use of math in everyday life restricted to be equal across genders. All other parameters were estimated freely. *$p < 0.05$; ***$p < 0.001$.

of math in everyday life, which matches expectations that follow from hypothesis 2c. For men, math anxiety however did not mediate the relation between skills and use of math in everyday life, which was contrary to expectations following hypothesis 2b. The absence of an effect of math anxiety is probably due to the very low reported levels of math anxiety by men in this sample ($M = 29$ with a possible range of 23–92). For women, high addition skills were related to an elevated level of perceived math competence, which was related to higher use of math in everyday life. Also, high addition skills were related to a lower level of math anxiety, and math anxiety was negatively related to use of math in everyday life. Hence, math anxiety and perceived math competence mediated the relation between math skills and use of math in everyday life for women, which matches expectations that follow from hypotheses 2b and 2c. It should however be noted that these correlational data provide the estimation of various mediation models. Indeed, estimating a mediation model with math anxiety as the outcome variable, math skills as the independent variable and use of math in everyday life as the mediating variable, resulted in the estimation of a significant mediation effect for women. Hence, drawing conclusions on causal relations is impossible using correlational data. The fact that various mediation models were possible (for women) does show the interrelatedness of math skills, math anxiety, perceived math competence, and use of math in everyday life.

DISCUSSION

In everyday life, mathematical thinking may benefit important choices, concerning for example medical and financial issues (Reyna and Brainerd, 2007). However, mathematical thinking might be hampered in various ways. In the current study, it was investigated whether math skills as well as affective (math anxiety) and motivational (perceived math competence) factors were related to men's and women's use of math in everyday life. The study was part of the Grand National Research on Math in the Netherlands and depended on voluntary registration of participants, which resulted in a sample size of over 500 adults. Gender differences in all measures were tested first. Results supported the hypotheses that women would report higher math anxiety and lower perceived math competence than men. Women also reported a lower use of math in everyday life. Unexpectedly, women's skills were estimated at a lower level than men's. Concerning the relationships, math skills and use of math in everyday life were positively related, as expected. For both women and men, the level of perceived math competence mediated the relation: Higher skills were associated with a higher sense of competence, which in turn was associated with more use of math in everyday life. Only for women, math anxiety also mediated the relation between math skills and use of math in everyday life: higher math skills were associated with lower math anxiety, which was related to a higher use of math in everyday life.

Females' higher level of reported math anxiety and lower level of perceived math competence, compared to males', is consistent with the majority of results of previous studies on gender differences in math anxiety (e.g., Hembree, 1990) and self-beliefs concerning math (e.g., Else-Quest et al., 2010; Cvencek et al., 2011). The gender gap may vary as a result of the sample characteristics (age, educational level, country, culture, and profession). In our sample, there was a higher percentage of men, compared to women, in technical professions, which reflects the underrepresentation of women in the science, technology, engineering and mathematics (STEM) professions in the Netherlands (www.cbs.nl). The relatively high percentage of males in technical professions might explain part of the gender gap found in this study. At least two explanations are possible. Either males in our sample were more technically skilled and had more technical interests than females in our sample, resulting in more technical jobs and possibly also reflected in higher math skills and use of math in everyday life. Hence, jobs and gender might be a confound. An alternative explanation would be that men indeed perform higher on the type of math test administrated in the current study. Higher skills might independently or dependently lead to lower math anxiety, higher perceived performance and more use of math in everyday life. It is striking that a gender gap in affective and motivational factors also exists in the current high-educated sample of adults. Note that also in general males tend to report lower levels of anxiety (e.g., Dyrbye et al., 2006) and higher levels of confidence (but see Britner and Pajares, 2006).

Females' lower estimate of addition skill, compared to males', was unexpected. The effect size of the difference was small, smaller than that of the gender differences regarding math anxiety and perceived math competence. The small effect size of the gender difference in math skills is in line with the literature, which is undecided and shows both female and male advantages on mathematics assessments. Situational differences may influence the direction of the advantage. Pressure and time limit may lower females' performance, in spite of an advantage in the classroom (Pomerantz et al., 2002). In the current study, the assessment was performed in a familiar, self-chosen environment, mostly in the participant's home. Estimates of ability were communicated to the participant only and had no consequences. These circumstances might reduce a possible gender difference in estimated ability. However, response time was limited, participants received accuracy feedback on each item, were rewarded for correct responses and penalized for mistakes and their estimated ability level was communicated to them. These aspects might increase a gender gap in estimated ability, in favor of males. In sum, although the assessment was set up as an assessment of addition skill, it might have been perceived of as a test of performance. It is unclear whether the gender difference should be perceived of as a male advantage of skill or of test-taking ability. Unknown is whether gender stereotypes about math played a role in the home situation. It has been found that these become activated in situations, resulting in more poorly performance of female (Spencer et al., 1999). Finally, the sample may have been biased if primarily those men who were confident of their math abilities chose to participate. Apart from these explanations for the gender gap in math skills, it should be noted that the difference was small. The modesty of the difference in skills however makes the larger gender difference in math anxiety and perceived math competence even more interesting: Despite only a small disadvantage in skills, women report higher math anxiety and lower perceived math competence than men.

Ashcraft et al. (2007) and Hopko et al. (2002) stress the importance of exercising skills to reach high performance. The observed relations in the present study may be interpreted as an illustration of this process and suggest that those who are weak at math should be provided with additional exercise because their weak skills may prevent them from using math in everyday life, missing out the required exercise. Moreover, Ashcraft et al. (2007) and Hopko et al. (2002) note that performance-based anxieties, like math anxiety, can hinder the exercise of skills. Indeed, in the current study, weak skills were associated with higher math anxiety, raising an extra barrier for practice. A downward spiral, linking skills, anxiety, exercise, and performance may emerge. Possibly, this is also reflected in the lower skills of women as they do not use it as often as men and also have professions more distant from technical jobs. However, note that data in the current study were correlational. Although the assessment of use of math in everyday life was related to both skills and math anxiety as well as perceived math competence, this does not imply that (experimentally) changing one of these factors would cause a change in any of the other factors.

Note that the most common professions in the present study were those in education, care, and welfare. In both types of professions, use of math is essential. Beilock et al. (2010) already showed the significance of teachers' own math anxiety for the development of their pupils' math skills. In medical professions, numeracy is essential as well, for example in calculating doses (e.g., McMullan et al., 2012). The present study shows the relevance of developing math skills as well as positive affect and feelings of competence for use of math in everyday life.

The current study is not without limitations. First, a proxy of math skills was used, using a computer-adaptive addition test. The selection of the addition test was based on high correlations with other math tests, but it remains an estimate, using time limits, automation of math facts, in only one domain. Second, the math anxiety questionnaire was based on school situations. As the initial aim of the study was to include child participants as well as adults, a children's questionnaire was used. Hence, participants were asked to fill in the questionnaire retrospectively. During the study, it turned out that participation from individuals under 18 years was low and in hindsight, an adult questionnaire might have been more appropriate. Replication with an adult math anxiety questionnaire is therefore desired. Even though, the correlation between the math anxiety questionnaire and estimated addition skills was comparable to what is reported in the literature and the selection of instruments for math anxiety and math skills seems justified. It would be interesting to study whether these correlations would hold using a questionnaire assessing state math anxiety instead of trait math anxiety. Goetz et al. (2013) showed important differences in the relation between math performance and math anxiety using either a trait or a state math anxiety assessment. Third, the questionnaire on the use of math in everyday life was developed from scratch for the current study. A challenge when developing such a questionnaire is to include only those situations that are applicable to all respondents. Although everyday life is full of math-related situations, these differ from person to person. Those responsible for a family face different challenges than for example students. Also, elderly people increasingly deal with medical situations and decisions and might use technology in a different way or may even lack any technological devices. In the current questionnaire, we started off with a range of situations. Statistical analysis showed that some questions were unrelated to the majority of the questions. Some subjects were relevant for only a small number of people. Also, in hindsight, some questions were more related to common knowledge and to keeping a budget than to the propensity to recognize and solve quantitative issues in real life situations. However, psychometric analyses detected these questions and the present questionnaire seems a good starting point. It can be improved by adding questions on the use of math when making medical and financial decisions, taking into account individual differences in everyday life. Moreover, technology is rapidly improving and people will adapt their use of math to the available technologies. For example, anticipating on the amount of change by looking for coins may not be so relevant in a world of digital payments. It should be considered from situation to situation whether full reliance on technological devices is possible or that mathematical thinking is still required to evaluate the outcomes of the device. Also, more exclusive answer options might be needed to cover the full range of individual differences in dealing with the situations described. Fourth, the present sample is self-selected and conclusions may be specific to this sample. The present data show that the current participants were relatively high-educated. Moreover, participants voluntarily visited the website of the Grand National Research on Math and it is very likely that they appreciated doing math. Participants could avoid the math skills test but only those who did take the test were included in the sample of the present study. Participants in the present sample may conceive of themselves as quite competent in math and less math-anxious than the general population. This hypothesis can only be tested in a replication study in a more general population. Importantly, the results on the gender gaps in math anxiety and perceived math competence and on the relationship between math anxiety and math skills are consistent with the majority of the results reported in the literature. The final and most critical drawback of the current study is its correlational nature. It is tempting to conclude that math skills cause math anxiety and/or the use of math in everyday life. However, all measurements were assessed under the same conditions, at the same time, without any manipulations and conclusions on causal relationships are impossible.

In sum, the present study supports the idea of a vicious circle linking skills, affective and motivational factors and use of math in everyday life, which has not been reported earlier in the literature. Individuals with high math skills use math more frequently in everyday life and are also more confident of their math abilities. For women, math anxiety is negatively related to using math in everyday life and to math skills. Use of math in everyday life, skills, affective and motivational factors may strengthen and mutually influence each other.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

Data for this study were collected in The Grand National Research on Math, which is an initiative of the Netherlands Organization for Scientific Research (NWO), and Dutch broadcasters NTR and VPRO.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.00513

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Conflict of Interest Statement: HV is scientific director of Math Garden, which was used to assess math skills. The other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 29 April 2016
doi: 10.3389/fpsyg.2016.00637

Different Sources of Threat on Math Performance for Girls and Boys: The Role of Stereotypic and Idiosyncratic Knowledge

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Keywords: stereotype threat, idiosyncratic effect, personal academic experiences, math performance, children

OPEN ACCESS

Edited by:
Bernhard Hommel, Leiden University, Netherlands

Reviewed by:
Gregoire Borst, Université Paris Descartes, France
Lorenza S. Colzato, Leiden University, Netherlands

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *22 July 2015*
Accepted: *16 April 2016*
Published: *29 April 2016*

Citation:
Régner I, Selimbegović L, Pansu P, Monteil J and Huguet P (2016) Different Sources of Threat on Math Performance for Girls and Boys: The Role of Stereotypic and Idiosyncratic Knowledge. Front. Psychol. 7:637. doi: 10.3389/fpsyg.2016.00637

For 20 years, the impact of stereotypical knowledge on math performance has been intensively investigated, especially within the framework of "stereotype threat" (Steele, 1997). Stereotype threat (ST) theory and research "do not focus on the internalization of inferiority images or their consequences. Instead, they focus on the immediate situational threat that derives from the broad dissemination of negative stereotypes about one's group—the threat of possibly being judged and treated stereotypically, or of possibly self-fulfilling such a stereotype" (Steele and Aronson, 1995, p. 798). Here, we distinguish between ST and another powerful yet relatively neglected factor in the determination of math performance: self-images of inferiority derived from personal history of failure. There is some evidence that such self-images of inferiority may also lead to under performance in math tests (hereafter referred to as idiosyncratic effects). One question that arises is whether and how ST and idiosyncratic effects interact with each other, which would offer a fuller picture combining the intervention of stereotypic and idiosyncratic knowledge in math performance.

ST EFFECTS

ST refers to a decrease in test performance in situations where individuals feel threatened by the possibility that their performance will confirm—to others, and/or themselves—a negative stereotype about their group abilities (Steele, 1997). This situational threat increases concern about being stereotypically judged and mistreated, which impairs processing efficiency and leads to underperformance (Schmader and Johns, 2003). Consistent with this, females underperform relative to equally qualified males on difficult math tests when told that the test is gender-biased or when simply told that it measures math skills, but perform as well as males when told that the test is gender-fair or when it is supposedly not diagnostic of math abilities (Spencer et al., 1999; for reviews see Ben-Zeev et al., 2005; Régner et al., 2014).

ST typically affects only a sub portion of the stereotyped group, those with the skills and self-confidence to have identified with the domain (Steele, 1997). On the contrary, less confident and less identified individuals, those who have internal doubts about their ability, are likely to underperform regardless of whether they are stereotype threatened in the situation. Consistent with this, ST effects have been mostly examined and found among high achieving females majoring in Math, Science, and Engineering (Spencer et al., 1999; Bell et al., 2003; Good et al., 2008; Régner et al., 2010) and high math-identified females (Cadinu et al., 2003; Keller, 2007). The myriad studies conducted since Steele and Aronson's (1995) seminal paper clearly demonstrate the influence of stereotypical knowledge in the math domain.

IDIOSYNCRATIC EFFECTS

If the influence of students' inferiority images derived from their own failures in math was not in the scope of stereotype threat theory, support for this idiosyncratic influence can be found in the literature on autobiographical memory. Some studies indicate that memories of personal academic successes or failures can be activated by the testing situation and then impact one's current performance (Monteil and Huguet, 1993, 1999). Monteil (1988, 1991) showed that students with past failures in math (low achievers) who publicly received a positive feedback on a preliminary math test obtained lower performance on a subsequent test when it was taken in a public rather than private context, as if they could not publicly deal with a positive feedback. The reverse pattern was obtained for high achievers having received positive feedback who then underperformed in the private (rather than public) context. In general, students facing inconsistencies between their own academic history and the testing situation (e.g., low achievers receiving positive feedback) are more self-focused, resulting in impaired task performance (Monteil et al., 1996; Brunot et al., 2000). In Huguet et al. (2001), students with past failures or successes (low vs. high achievers) in math were asked to learn a complex figure, and to reconstruct it from memory on paper. They were either told the test would measure their ability in geometry or in drawing. Whereas, low achievers underperformed relative to high achievers in the geometry condition, low and high achievers performed equally well in the drawing condition. Low achievers' performance was thus inhibited when the task characterization referred to a domain associated with past generalized failures while the test was exactly the same in both contexts.

Selimbegović et al. (2011) went a step further by activating and measuring autobiographical memories of success vs. failure, while distinguishing between general and specific memories. Before taking a math test, participants had to recall three general vs. specific autobiographical memories of either their past academic successes or failures. General memories of failure and specific memories of success resulted in worse math performance than general memories of success and specific memories of failure. Additionally, general memories of failure and specific memories of success induced fear of failure (Selimbegović et al., 2011) or threat appraisal (Selimbegović et al., 2015), with increased fear of failure playing a mediating role in performance. In sum, knowledge about one's past academic performances can induce counterproductive self-focus, fear of failure, threat appraisal, and impaired performance. This is enough evidence to consider idiosyncratic knowledge as another potential threat for math performance.

CURRENT RESEARCH

Whether and how ST and idiosyncratic effects interact remains unexplored. We examine this issue with a reanalysis of Huguet and Régner's (2009) ST study. Compared with the other studies reported above, this research has the advantage to provide all necessary measures to simultaneously test ST and idiosyncratic effects. It comprised both male and female participants (the sex-ratio of samples used in previous "idiosyncratic effects" studies did not allow to test for ST), used the same geometry/drawing paradigm as in Huguet et al.'s (2001), comprised students' math grades and a measure of their perceived personal reputation in terms of "good" vs. "bad" students in math.

Consistent with ST theory, Huguet and Régner (2009) found a significant gender by task characterization interaction: whereas girls underperformed compared to boys in the geometry condition, they outperformed boys in the drawing condition (See also Huguet and Régner, 2007). Assuming that ST and idiosyncratic effects interact with each other, low-achieving girls in the geometry condition (cumulating the threats related to their own personal academic experiences and gender group) would obtain the worst performance. However, this hypothesis is hardly compatible with ST theory that predicts ST to have its greatest effect on the better, more confident students in stereotyped groups. An alternative could be that ST and idiosyncratic effects do not interact but occur simultaneously. This would imply the coexistence of both effects in the same data set: girls underperforming relative to boys in the geometry condition, while outperforming them in the drawing condition, and the low achievers (both genders) underperforming relative to high achievers in the geometry condition, while performing equally well as them in the drawing condition.

FURTHER ANALYSIS OF HUGUET AND RÉGNER'S (2009) DATA

The participants were 199 French middle-school students (92 girls and 107 boys, mean age = 12.12, $SD = 0.70$). Like in Huguet et al. (2001), they had to learn a complex figure (made of 22 units) and then to reconstruct it from memory on paper. Students were either told the test would measure their ability in geometry or in drawing. Recall performance was measured in terms of both the number and quality of the units reproduced from the complex figure. Two points were given if the unit was correct and properly positioned, 1 point if it was either altered but correctly placed or not altered but incorrectly placed, 0.5 point if it was altered and in a wrong place, and 0 if it was missing or unrecognizable. The possible scores could range from 0 to 44 (Grand Mean = 23.37; $SD = 6.09$; $min = 4.50$ and $max = 40$). Students' math grades were available from the school records on a scale ranging from 0 to 20 (Grand Mean = 12.15; $SD = 3.89$; $min = 2.30$ and $max = 19$). The present reanalysis required using Task characterization, students' Gender and Math grades as predictors in order to test ST effects (Gender × Task characterization interaction), idiosyncratic effects (Students' grades × Task characterization interaction), and the three-way interaction.

Since, contrary to Huguet et al. (2001), participants in Huguet and Régner (2009) had not been selected a priori on the basis of their achievement level in Math, it was important here to make sure that those with lower vs. higher math grades were aware of their inferiority vs. superiority in this domain. For that purpose, we used Huguet and Régner's (2009) measure of students' perception of their personal reputation in terms of "good" vs. "bad" student in Math within their class. Students answered two items: "Among your classmates, how many think you're a good student in Math ?" (item 1) and "How many classmates think you are not good in Math ?" (item 2), using a 5-point Likert scale ranging from 1(none) to 5 (everybody). These items were subtracted to distinguish between students considering they had a good or bad reputation in math and those considering they were average or with no specific reputation. Any score different from zero means that students considered they had either a relatively good or bad reputation, which was the case of most participants (63.3%). Participants whose perception of personal reputation was average or unclear (score equal to zero), were removed from our reanalysis. Therefore, the distinction between low vs. high achievers did not rely exclusively on students' math grades but also on students' perception of their personal reputation in math, while excluding both average students and those reporting no clear personal reputation in that domain. The final sample included 126 participants, with 57 girls (25 in the Geometry condition and 32 in the Drawing condition) and 69 boys (41 in the Geometry condition and 28 in the Drawing condition).

RESULTS

We regressed students' recall performance on gender (boys = 0, girls = 1), task characterization (drawing = 0, geometry = 1), math grades (mean-centered), and their interaction terms. The Gender by Task characterization interaction was significant, indicating the presence of a ST effect unfavorable to girls [(Huguet and Régner, 2009), $b = -5.22$, $SE = 2.08$, $t_{(117)} = -2.50$, $p = 0.014$]. Although, the Students' grades by Task characterization interaction did not reach significance [$b = 0.58$, $SE = 0.38$, $t_{(117)} = 1.53$, $p = 0.128$], the three-way interaction did, $b = -1.19$, $SE = 0.55$, $t_{(117)} = -2.17$, $p = 0.032$ (**Figure 1**). We used Preacher et al.'s (2006) interactive calculation tools to probe this interaction by estimating simple slopes at low (−1 *SD*) and high (+1 *SD*) values of our continuous predictor (math grades). We also used Keppel's modified Bonferroni correction to control for error rate with planned comparisons (Keppel, 1991), which led to consider only two simple slopes as significant. In line with ST theory, the higher math grades, the stronger ST effect: girls underperformed relative to boys in the Geometry condition, $b = -5.83$, $SE = 2.12$, $t_{(117)} = -2.75$, $p = 0.007$, whereas girls and boys performed equally well in the drawing condition. An idiosyncratic effect also occurred but only among boys: the lower achievers underperformed relative to the higher achievers in the geometry condition, $b = 0.49$, $SE = 0.22$, $t_{(117)} = 2.29$, $p = 0.024$, whereas the lower and higher achievers performed equally well in the drawing condition.

DISCUSSION

The present findings provide first evidence that both stereotype threat and idiosyncratic effects can occur in children without cumulative effects: stereotype threat occurred among high-achieving-girls, while the idiosyncratic effect occurred in low-achieving boys. Using math grades as a moderator (rather than a covariate to adjust the outcome for prior performances or an inclusion criterion to select talented students as it is usually the case in stereotype threat studies), we found that stereotype threat is more likely in girls with higher math grades. This result is consistent with Steele's (1997) basic argument that stereotype threat typically affects the higher achievers, those with the skills and self-confidence to have identified with the domain. Interestingly, neither students' achievement level nor their domain identification were taken into account in recent meta-analyses (Stoet and Geary, 2012; Flore and Wicherts,

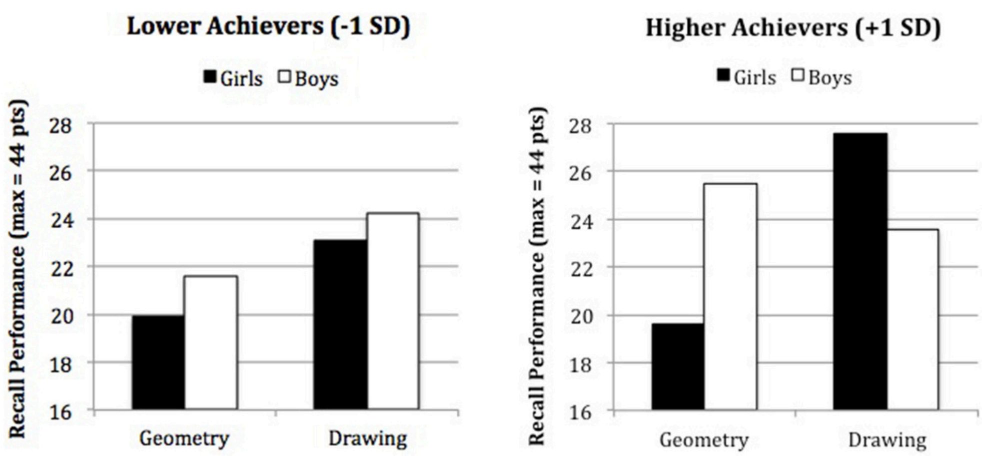

FIGURE 1 | Recall performance as a function of Gender and Task Characterization for lower (−1 *SD*) and higher (+1 *SD*) achievers in Math.

2014) that downplayed the seriousness of ST effects. Although, we agree with these papers that the importance of ST effects should not be overstated, we also think that the key moderators of these effects should not be underestimated either. In their meta-analytic review, Walton and Cohen (2003) clearly found that both ST (as well as stereotype lift effects) are much more likely among stigmatized who are high achievers and/or highly identified with the domain. Consistent with this, in our own female sample the higher the math grades, the higher ST effect.

On the contrary, why girls did not experience idiosyncratic effects is difficult to explain. The negative math-gender stereotype is so powerful that it may have overcome the influence of other sources of threat like inferiority images derived from one's personal academic experiences. Girls' self-construal being mostly interdependent and boys' self-construal mostly independent (Markus and Kitayama, 1991; Huguet and Monteil, 1995; Keller and Molix, 2008), girls may be especially sensitive to collective reputations and boys to personal reputations. Although, the dissociation found here between stereotype threat and idiosyncratic effects needs to be better understood, it seems that inferiority images rooted in stereotypic vs. idiosyncratic knowledge are different sources of threat on math performance. This is an important conclusion as the exact relationships between ST and other sources of threat such as self (rather that group)-images of inferiority in math (or other domains) remained unexplored so far. In line with ST theory (Steele, 1997), ST research indeed focused on high achievers and neglected those with self-images of inferiority (i.e., low achievers). However, in parallel, some studies in the past 25 years provided evidence that self-images of inferiority also lead to underperformance in math tests (e.g., Monteil and Huguet, 1999; Selimbegović et al., 2011, 2015). The time has come to integrate both literatures. The present re-analysis is a first step in this direction.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer LC and handling Editor declared their shared affiliation, and the handling Editor states that the process nevertheless met the standards of a fair and objective review.

frontiers in Psychology

ORIGINAL RESEARCH
published: 03 November 2015
doi: 10.3389/fpsyg.2015.01597

Parent-child math anxiety and math-gender stereotypes predict adolescents' math education outcomes

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Two studies examined social determinants of adolescents' math anxiety including parents' own math anxiety and children's endorsement of math-gender stereotypes. In Study 1, parent-child dyads were surveyed and the interaction between parent and child math anxiety was examined, with an eye to same- and other-gender dyads. Results indicate that parent's math anxiety interacts with daughters' and sons' anxiety to predict math self-efficacy, GPA, behavioral intentions, math attitudes, and math devaluing. Parents with lower math anxiety showed a positive relationship to children's math outcomes when children also had lower anxiety. The strongest relationships were found with same-gender dyads, particularly Mother-Daughter dyads. Study 2 showed that endorsement of math-gender stereotypes predicts math anxiety (and not vice versa) for performance beliefs and outcomes (self-efficacy and GPA). Further, math anxiety fully mediated the relationship between gender stereotypes and math self-efficacy for girls and boys, and for boys with GPA. These findings address gaps in the literature on the role of parents' math anxiety in the effects of children's math anxiety and math anxiety as a mechanism affecting performance. Results have implications for interventions on parents' math anxiety and dispelling gender stereotypes in math classrooms.

Keywords: math anxiety, gender stereotypes, gender, parents, math education

OPEN ACCESS

Edited by:
Erin Anne Maloney, University of Chicago, USA

Reviewed by:
Zhe Wang, The Ohio State University, USA
Macarena Suárez Pellicioni, University of Barcelona, Spain

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *27 June 2015*
Accepted: *02 October 2015*
Published: *03 November 2015*

Citation:
Casad BJ, Hale P and Wachs FL (2015) Parent-child math anxiety and math-gender stereotypes predict adolescents' math education outcomes. Front. Psychol. 6:1597. doi: 10.3389/fpsyg.2015.01597

INTRODUCTION

The status of math education in the US is cause for concern. Standardized math test performance indicates the US is ranked 35th out of 64 countries (National Center for Education Statistics, 2012). Politicians, educators, and researchers may point the blame at the US system of higher education, but another source should share the blame: our math-phobic culture (Burns, 1998; Chew and Dillon, 2014). Many Americans report fear or anxiety about conducting math and many students shy away from math-intensive disciplines such as the sciences, technology (e.g., computer science), engineering, and of course, mathematics and statistics (STEM; Meece et al., 1990; Chipman et al., 1992). Many Americans report that they just do not like math and statistics. This is problematic as mathematics is a gateway field for STEM disciplines and societal advancement in technology and science (Roman, 2004). If the majority of Americans are afraid of math, as a country we face falling further behind our math-friendly counterparts.

This social problem leads researchers and educators to ask why, where does this math anxiety originate? Math anxiety can be defined as "feelings of fear, apprehension, or dread that many people experience when they are in situations that require solving math problems" (Maloney et al., 2014, p. 404). Research on adolescents' math anxiety has pointed to parents, teachers, and peers as major environmental sources (Wigfield and Eccles, 2000; Beilock et al., 2010; Gunderson et al., 2012). We learn our math phobia in part from important others who influence our early life development. Another potential source of math phobia that has received research attention is cultural stereotypes about gender and math (Steffens et al., 2010; Cheryan, 2012). Despite evidence that the gender gap in math performance in the US has disappeared (Hyde et al., 2008; Lindberg et al., 2010), cultural biases about the superiority of boys and men in math permeate our social consciousness. Media attention has proscribed disparaging comments about girls' and women's inferiority in math and science (e.g., former Harvard President Lawrence Summers and Nobel Laureate Tim Hunt; Bombardieri, 2005; Associated Press, 2015). Yet, these cultural influences have lasting effects and will likely remain pervasive for years to come, as research shows stereotype change is a slow process (Devine and Elliot, 1995) and public attitudes are slow to change following cultural shifts (e.g., Civil Rights Movement and school desegregation; Newport et al., 1999).

The purpose of the present studies is to further probe the social determinants of adolescents' math anxiety by examining the relationship between math anxiety from same and other-gender parents with children's math anxiety and how this relates to math education outcomes. Parents' math anxiety is conceptualized as a moderator, determining the strength and direction of the relationships between children's math anxiety and math education outcomes. A plethora of research has examined the relationship between parents' (primarily mothers') math-gender stereotypes and perceptions of their child's math abilities with children's math attitudes and math anxiety (Eccles and Jacobs, 1986; Yee and Eccles, 1988; Midgley et al., 1989; Eccles et al., 1990; Jacobs, 1991, 2005; Jacobs and Eccles, 1992); however, little research has examined parents' own math anxieties (Gunderson et al., 2012; see Maloney et al., 2015). Addressing this gap in the literature, this study examines parents' own math anxiety and how it interacts with children's math anxiety to predict math education outcomes. Further, the first study examines these relationships within same- and mixed-gender parent-child dyads to explore the gendered nature of the intergenerational transmission of math anxiety (e.g., see for example Gniewosz and Noack, 2012). Addressing a call for a mechanistic approach (Gunderson et al., 2012), the second study examines children's math-related gender stereotypes as a source of math anxiety and tests math anxiety as a mechanism through which math-gender stereotypes negatively influence math outcomes for *both* girls and boys. The math education outcomes examined herein include math self-efficacy, math attitudes, math devaluing, math education behavioral intentions, and classroom math performance (GPA).

Teachers and Parents as Sources of Math Anxiety

Eccles et al. (1983) developed an Expectancy-Value Theory of achievement motivation, originally in mathematics, that describes various cultural, social, interpersonal, and individual factors that influence children's motivations, task values, expectations for success, and achievement related choices. Included in the cultural milieu factors are cultural stereotypes about the subject and occupation (e.g., mathematics) and socializers' (e.g., parents) beliefs and behaviors, as well as children's own perceptions of socializers' beliefs and society's stereotypes about the domain. The Expectancy-Value Theory has received extensive support over the past few decades (see Wigfield and Eccles, 2000, for a review). Thus, the role of parents in influencing children's values, beliefs, expectations, performance, and choice in the math domain is well-known.

Both teachers and parents play a major role in socializing children's academic values and attitudes and an extensive body of research documents how parents' and teachers' expectations, gender stereotypes, and attributions impact children's math attitudes and performance (Yee and Eccles, 1988; Eccles et al., 1990; Tiedemann, 2000; Jacobs, 2005). Interestingly, however, little research has examined teachers' and parents' own math anxiety as an antecedent for children's math anxiety, attitudes, and achievement. A recent study found that female teachers' math anxiety impacted early elementary school girls', but not boys', math achievement and attitudes (Beilock et al., 2010). Specifically, girls whose teacher had higher math anxiety had lower math grades and learned less content at the end of the year compared to girls whose teacher had lower math anxiety, even after controlling for girls' math achievement in the beginning of the school year. It seems math-anxious teachers reinforced math-gender stereotypes as girls' endorsement of math-gender stereotypes mediated the effect of teacher anxiety on their math performance. A study with second grade elementary children examined parents' math anxiety in relationship to children's math anxiety, activities, and academic self-perceptions, but found no effects (Jameson, 2014). This work suggests the need for continued investigation of the role of parents' anxiety in children's anxiety in various developmental stages to determine when this effect begins. The only known study to find an effect of parents' math anxiety on their first and second grade child's math anxiety is a recently published study (Maloney et al., 2015). Thus, the present study focuses on parents' math anxiety as a socializing agent of children's math anxiety and the downstream effects on math education outcomes.

One reason researchers may have ignored the role of parents' anxiety in developing children's math anxiety and performance is a common (mis)perception that math learning is more likely to take place during school than at home and the role of parents may be less critical than teachers in math learning (Cannon and Ginsburg, 2008). However, just as teachers serve as role models for students, parents serve as long-term role models and their beliefs can influence their children as children develop their own identities, values, and efficacy (Yee and Eccles, 1988; Eccles et al., 1990; Tiedemann, 2000; Jacobs, 2005). Another potential reason for this gap in the literature is that people may not think about parents computing math, unless it is part of their occupation (e.g., accounting, banking). In contrast, school is the domain in which math is learned and regularly used and teachers perform mathematical problems publically in front of students and therefore seem to have more direct influence on children's math attitudes and anxiety. However, parents, regardless of their profession, likely perform more mundane mathematical computations on a regular basis such as making a household budget, balancing a checkbook, and calculating a tip at a restaurant, which can elicit math anxiety (Ashcraft, 2002). Parents' math anxiety may be subtly communicated to children through these mundane activities, or even more directly in their role of helping (or not helping) children with their math homework (Bhanot and Jovanovic, 2005; Maloney et al., 2015).

Does Parent Gender Matter?

Beilock et al. (2010) found that female teachers' math anxiety affected girls' math anxiety, performance, and amount of math learning over a school year, but it did not affect boys. This raises the question of the gender dynamics of math attitude, anxiety, and math-gender stereotype transmission between teachers and students and parents and children. Beilock et al. (2010) did not examine effects of male teachers, likely because more than 90% of elementary school teachers are female, and this is a new area of research, thus the effect of teacher gender remains a question for investigation. Likewise, only one published study has examined the effect of parents' math anxiety on children's math anxiety and achievement (Maloney et al., 2015), but sample demographics did not allow for a gender analysis, thus the question of parent gender is also yet to be addressed.

A great deal of the research using an expectancy-value framework focuses on the transmission of math-gender stereotypes from parents to children and how stereotypes influence children's achievement outcomes. This body of work has examined the gender of parents, particularly in the transmission of their math-gender stereotypes and math attitudes, but not specifically their math anxiety. This literature can inform questions and hypotheses about the gender composition of parent-child dyads in the intergenerational transmission of math anxiety. For example, is the influence of mothers to daughters and fathers to sons greater than mixed-gender transmission of mothers to sons and fathers to daughters? Research has mostly supported the same-gender dyad model such that mothers in particular communicate math-gender stereotypes to their daughters (O'Bryan et al., 2004), which subsequently predicts daughters' academic and career choices, even several years later (Bleeker and Jacobs, 2004). For example, if mothers endorse math-gender stereotypes that men are superior to women in math, they may communicate this (intentionally or unintentionally) to their daughters, who then may show less interest in math and choose other academic and career domains. Indeed, girls' and women's choices of academic and career trajectories is one explanation for the underrepresentation of women in STEM, rather than a lack of ability explanation (Wang et al., 2013). Many girls and women who show high aptitude in multiple domains choose academic and career paths outside of STEM in part because they have more opportunities available to them (Wang et al., 2013).

There are several reasons we hypothesize that same-gender parent-child transmission of math anxiety is more common than mixed-gender transmission. First, women and girls tend to experience greater math anxiety than men and boys (Hembree, 1990; Ramirez et al., 2013), regardless of their actual math ability (Hyde et al., 1990; Meece et al., 1990; Devine et al., 2012), and it begins as early as first and second grade (Harari et al., 2013; Ramirez et al., 2013) and increases as children get older (Hembree, 1990). Currently about 20% of the population is characterized as high in math anxiety (Eden et al., 2013). If women are more likely to suffer from math anxiety than men, then it is logical to predict that mothers experience greater math anxiety than fathers and likely communicate this to their children, particularly daughters, who also are more likely to have high math anxiety than sons. Second, gender role socialization most commonly occurs with same-gender caregivers (Bussey and Bandura, 1984). During development, daughters may be more likely to pick up on mothers' math anxiety than fathers', and sons from fathers rather than mothers. Of course there are children who strongly identify with other-gender parents and may more quickly adopt their beliefs, values, and attitudes (e.g., daddy's girl or mama's boy; Gniewosz and Noack, 2012). Finally, parents often hold gender stereotypes about their children's performance in math, believing that sons' have stronger math ability than daughters, even when there is no evidence to support this belief (Furnham et al., 2002). As a result, parents may expect daughters to perform more poorly in math, which may contribute to greater math anxiety for girls.

Antecedents and Effects of Math Anxiety

There is a large body of literature documenting the negative effects of math anxiety; however, there is still much we do not know. The majority of research focuses on negative consequences rather than antecedents and contexts in which math anxiety develops (Ashcraft and Ridley, 2005; Jameson, 2014; Maloney et al., 2015), and more research is needed with children (Jameson, 2014). Recent research has documented cognitive and biological antecedents of math anxiety including diminished working memory capacity, low math ability, attentional bias, and genetic factors (Wang et al., 2014; Suárez-Pellicioni et al., 2015).

The present studies examine an environmental factor, specifically parents' anxiety as a moderator of adolescents' math anxiety, thus helping to fill this gap in the literature.

Several negative consequences of math anxiety include avoidance of mathematics (e.g., math courses and math-intensive careers), less confidence, lower math self-efficacy, and more negative attitudes toward math (Hembree, 1990; Ashcraft et al., 1998; Ashcraft, 2002). Avoidance of math courses and math-intensive careers may be one explanation for the gender gap in STEM careers (Wigfield and Eccles, 2000; Gunderson et al., 2011; Cheryan, 2012). Math anxiety causes lower math performance, regardless of actual math ability (Hembree, 1990; Maloney and Beilock, 2012; Park et al., 2014).

Another negative consequence of math anxiety is low math self-efficacy. Self-efficacy is the confidence that one has the ability to succeed in the domain (Schunk, 1981, 1982a,b; Pajares, 1996). Although research clearly demonstrates the importance of math self-efficacy in math achievement and attitudes, few studies have examined how self-efficacy relates to math anxiety (Jameson, 2014). Two studies have found a negative relationship between math self-efficacy and math anxiety (Meece et al., 1990; Cooper and Robinson, 1991). Math anxiety was directly related to both boys' and girls' math ability perceptions, but interestingly, not to math grades (Meece et al., 1990). Given the importance of reducing students' math anxiety in order to promote positive math achievement and attitudes, many studies have examined ways that parents can help reduce children's math anxiety (e.g., Vukovic et al., 2013).

Overview of Studies

The current studies address different gaps in the literature by exploring antecedents of math anxiety: parents' math anxiety (Study 1) and math-gender stereotypes (Study 2), and a mechanistic (mediational) perspective of math anxiety (Study 2). Study 1 posits an interaction between parent and children's math anxiety in predicting several math education outcomes including math self-efficacy, math attitudes, math devaluing, math education behavioral intentions, and math GPA. These relationships are tested within the dyadic relationships of parents and children and the gender of parent and child dyad is examined for similar and different patterns in math education outcomes. Study 2 examines children's endorsement of math-gender stereotypes as an antecedent of math anxiety, and tests math anxiety as a mechanism through which math-gender stereotypes negatively influence math outcomes for *both* girls and boys.

STUDY 1

Hypotheses

Based on the literature reviewed we predict (1) main effects of child's math anxiety on the outcome variables. Specifically, greater math anxiety will predict (1a) lower math self-efficacy, (1b) lower math GPA, (1c) lower math education behavioral intentions, (1d) more negative math attitudes, and (1e) greater math devaluing. We predict (2) an interaction between parents' and children's math anxiety such that higher levels of children's math anxiety will be negatively correlated with math education outcomes, and the correlations will be strongest when parents also have higher math anxiety. Finally, we predict that (3) same-gender parent-math dyads are most likely to show significant relationships between math anxiety and education outcomes (both positive and negative), particularly (3a) mother-daughter dyads. Relatedly, (3b) we expect mothers and daughters to show patterns indicative of higher anxiety than other parent-child dyads. We expect (3c) few if any significant relationships for mixed-gender dyads including mother-son and father-daughter.

Method

Participants

A total of 1342 parents were recruited and 683 participated[1], resulting in a 51% response rate. Student participants included 377 (55%) girls and 306 (45%) boys in 6th ($n = 157$, 23%), 7th ($n = 291$, 43%), or 8th ($n = 235$, 34%) grade honors ($n = 366$, 55%) or standard math ($n = 298$, 45%) classes (e.g., Algebra Readiness, Pre-Algebra, or Algebra)[2]. Students' ages ranged from 11 to 14 reflecting ages in the 6th through 8th grades. There were 8 middle schools from southern California with 24 math teachers participating. Dyad types consisted of Mother-Daughter ($n = 315$, 46%), Mother-Son ($n = 239$, 35%), Father-Daughter ($n = 62$, 9%), and Father-Son ($n = 67$, 10%). The majority of students ($n = 538$, 88%) were born in the US. In contrast, the majority of parents were born outside the US (62%, $n = 419$). The majority of students and parents born outside the US were born in Mexico, South America, or an Asian country (e.g., China, Cambodia, Vietnam, Philippines). Students' self-reported race/ethnicity included 66% ($n = 435$) Latino/a or Hispanic, 10% ($n = 62$) Asian/Pacific Islander, 9% ($n = 58$) multiracial, and less than 5% each of Black/African American, Native American, White/Caucasian, or other. Parents' self-reported race/ethnicity included Latino/a or Hispanic 73% ($n = 486$), 10% ($n = 65$) Asian/Pacific Islander, 7% ($n = 47$) White/Caucasian, 7% ($n = 45$) Black/African American, and less than 5% of each group Native American, multiracial, or other. Parents' ages ranged from 22 to 63 ($M = 42.20$, $SD = 6.73$). Parents' education and household income are shown in **Table 1**.

TABLE 1 | Parents' education and household income.

Level of education	Mother $N = 525$	Father $N = 121$	Household income (in thousands)	Mother $N = 211$	Father $N = 72$
8th Grade or less	13.9%	8.3%	<5	20.4%	8.3%
9th–12th Grade	15.8%	14.0%	5–9999	5.2%	1.4%
HS Graduate	23.2%	20.7%	10–14,999	13.7%	11.1%
Some College	28.0%	26.4%	15–24,999	15.6%	5.6%
College Graduate	14.7%	22.3%	25–34,999	21.8%	13.9%
Post Graduate	4.4%	8.3%	35–49,999	9.5%	22.2%
Missing information (excluded from calculations)	5.2%	6.2%	50–74,999	8.1%	22.2%
			75 or more	5.6%	15.3%
			Missing Information (excluded from calculations)	61.9%	44.2%

Values are rounded to one decimal place for ease of reading. HS, High school education; Some College, attended college but did not complete a degree. Income is household income in thousands per year.

Materials

The students' questionnaires contained items assessing math anxiety, math self-efficacy, math education behavioral intentions, math attitudes, and math devaluing. Math class GPA was

[1]There were some marginal and significant differences in the characteristics and demographics of the students whose parent participated compared to students whose parent did not participate. Students without a participating parent had lower self-efficacy, and marginally greater endorsement of gender stereotypes and math. However, there were no significant differences for math anxiety, math attitudes, math devaluing, and math behavioral intentions. There was a marginal difference in the gender of the child such that females were more likely to have had a parent participate than males. There was a difference in the race of the child such that racial non-minority students, that is Caucasians or Asian Americans, were more likely to have had a parent participate than minority students. There were no differences for GPA, class type (honors/non honors) or grade level. See the Supplemental Results for the analyses.

obtained directly from the teacher. Parents' questionnaires contained a variety of similar measures, but only parents' math anxiety data are reported here.

Children's math anxiety was assessed by 3 items rated on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree;* based on Marx and Stapel, 2006). Items included "I often get nervous when I have to do math," "Many times when I see a math problem I just 'freeze up'," and "I have never been as good in math as I am in other classes." The items had acceptable internal consistency ($\alpha = 0.731$) and were averaged so that higher values represented greater anxiety.

Parents' math anxiety was assessed by 2 items rated on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree;* based on Marx and Stapel, 2006). Items included "Many times when I see a math problem I just 'freeze up'," and "I have never been as good in math as in other classes in high school." The items were moderately to highly correlated, $r_{(558)} = 0.548$, $p = 0.001$ and were averaged so that higher values represented greater anxiety.

Children's math self-efficacy was measured by 5 items rated on a scale from 1 (*Not at all Confident*) to 6 (*Very Confident;* based on Zimmerman and Martinez-Pons, 1988). Sample items included "How confident are you that you will pass your math class at the end of the term?" "How confident are you that you will pass math at the end of this term with a grade better than a B?" and "How confident are you that you will get an A?" The items had acceptable internal consistency ($\alpha = 0.898$) and were averaged so that higher values represented greater math self-efficacy.

Children's math education behavioral intentions were measured by 6 items rated on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree;* adapted from Sparks et al., 1997; Butler, 1999). Sample items included "I plan to take more math classes than I have to in high school," "I plan to complete all of my math homework on time," and "I plan to participate in school related activities about math (like competitions or projects)." The items had acceptable internal consistency ($\alpha = 0.749$) and were averaged so that higher values represented greater math education behavioral intentions.

Children's math attitudes were measured by 5 items rated on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree*; adapted from Sparks et al., 1997; Butler, 1999). Items included "I will use math a lot when I grow up", "I enjoy studying math," and "I think math is boring" (reverse-scored). The items had acceptable internal consistency ($\alpha = 0.761$) and were reverse scored and averaged so that higher values represented more positive math attitudes.

Finally, children's math devaluing (Major and Schmader, 1998) was assessed by 5 items rated on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree*). Sample items included "I always feel good about myself when I do well on a math test" (reverse-scored) and "Doing well on math tests is very important to me" (reverse-scored). The items had acceptable internal consistency ($\alpha = 0.770$) and were reverse-scored and averaged so that higher values represented greater math devaluing.

Procedure

Institutional Review Board approval was obtained from California State Polytechnic University, Pomona and permission was granted by the District Superintendent, each school principal, and each participating school teacher. Parents provided consent forms indicating whether their child could participate, and also signed a consent form if they participated in the questionnaire. Finally, students provided consent/assent forms in class if they chose to participate.

Researchers visited the classroom during the designated period and distributed the questionnaires, which were available in both English and Spanish. After students completed the questionnaires, they were each given a packet containing a consent form and questionnaire to take home to give to one of their parents. Completed parent questionnaires were typically mailed back to the researchers in a pre-paid enveloped or returned to the teacher and later collected by the researchers.

Analysis Strategy

Although all of the relationships of interest exist at the student and parent level, the data came from an inherently hierarchical structure of children/parents (Level 1) nested within classrooms (Level 2) with different teachers, nested within different schools (Level 3). This sort of hierarchical structure often results in correlations of residuals among nested units that can bias the outcome of an ordinary least squares (OLS) regression by underestimating standard errors (Snijders and Bosker, 2011). Multilevel modeling (Raudenbush and Bryk, 2002) offers an appropriate remedy for analyzing nested data and is able to accommodate a wide range of data structures, including circumstances where the focal variables of interest are all situated on one level and the clustering is only a nuisance that prevents the use of OLS regression. To that end, two-level random intercept models were computed using the restricted maximum likelihood estimation, which adjusts for unequal sample sizes and is ideal for smaller datasets, with variance components estimator in SPSS Mixed Models Version 21 (IBM Corp., 2012). We were not able to use a three-level model because the number of schools ($N = 8$) was too small for a cluster analysis. However, the number of teachers ($N = 24$) was adequate for a two-level model to capture the nested nature of the data.

In addition, the data are also dyadic and non-independent as parents of the children also completed the questionnaire. The data were organized using the standard dyadic design and analyses are computed within dyad rather than between individuals (Kenny et al., 2006). For dyadic data, the slopes (the effects of predictors on Y for each dyad) are fixed to be equal across all dyads (Kenny et al., 2006). Instead the data are modeled through variation in the intercept at the Level 2 variable (teacher) across dyads. Finally, the Satterthwaite approximation was used to calculate degrees of freedom (Kenny et al., 2002).

For each model, the student's grade level and type of math class (honors or standard) were treated as control variables. Dyad type, child's math anxiety, and parent's math anxiety were entered into the model as main effects. Dyad type was effects coded as 1, 0.5, −0.5, and −1 for Father-Son, Father-Daughter, Mother-Son, and Mother-Daughter, respectively. To facilitate interpretation, child and parent math anxiety were group mean centered. All possible two-way interactions between the three variables were also entered into the model, as was a three-way interaction between dyad type, child's math anxiety, and parent's math anxiety. Significant interactions were graphed depicting the continuous variables (child and parent math anxiety) at one standard deviation above, at the mean, and one standard deviation below the mean (Aiken and West, 1991). Results for non-significant analyses are reported in the Supplementary Materials.

Results

Descriptive statistics for all study variables are provided in **Table 2** and the correlation matrix is displayed in **Table 3**. None of the variables were skewed or kurtotic to the extent that transformations were required.

Math Self-efficacy

The model predicting child's math self-efficacy indicated main effects of grade level, dyad type, and child's math anxiety, as well as the predicted three-way interaction between dyad type, child's math anxiety, and parent's math anxiety [$F_{(3,\ 577.13)} = 3.311$, $p = 0.020$; see **Table 4**]. The main effect of grade level indicated sixth grade students had higher math self-efficacy than seventh or eighth grade students ($\beta = 0.291$, $p = 0.051$); however, this effect was marginal and not of theoretical interest. The main effect of dyad type showed marginally lower math self-efficacy in the Mother-Daughter dyad compared to the other dyads ($\beta = -0.312$, $p = 0.062$). The main effect of child's math anxiety indicated a negative relationship such that greater math anxiety is associated with lower math self-efficacy ($\beta = -0.472$, $p = 0.003$), supporting Hypothesis 1a. However, both these main effects are subsumed in the three-way interaction. The three-way interaction model showed a significant relationship only for the Mother-Daughter dyad, supporting hypothesis 3a ($\beta = 0.379$, $p = 0.037$; see **Figure 1**). Daughters with lower math anxiety had higher math self-efficacy than daughters with higher math anxiety, and this relationship was stronger at lower levels of mother's anxiety ($b = -0.512$, $p = 0.001$), supporting Hypothesis 2 (Moderate mother anxiety: $b = -0.380$, $p = 0.001$; Higher mother anxiety: $b = -0.248$, $p = 0.006$). However, daughters with higher math anxiety had lower math self-efficacy when mothers had lower math anxiety, contrary to Hypothesis 2. There were no three-way interactions for other Parent-Child dyads (see Supplementary Results).

TABLE 2 | Descriptive statistics of study variables.

	M	*SD*	Range	Skew	Kurtosis
Child math anxiety	2.932	1.039	1–6	0.037	−0.233
Parent math anxiety	3.124	0.929	1–6	−0.048	0.070
Math self-efficacy	4.523	1.107	1–6	−0.752	0.077
Math GPA	2.267	1.204	0–4.30	−0.213	−0.824
Math behavioral intentions	4.471	0.801	1.33–6	−0.350	0.387
Math attitudes	4.384	0.973	1–6	−0.324	−0.076
Math devaluing	2.032	0.816	1–5.60	0.742	0.572

For Child and Parent Math Anxiety, Math Behavioral Intentions, Math Attitudes, and Math Devaluing, 1 = Very Strongly Disagree and 6 = Very Strongly Agree. For Math Self-Efficacy, 1 = Not at all Confident and 6 = Very Confident.

Math Class GPA

The model predicting child's math class GPA indicated main effects of class type and child's math anxiety, a two-way interaction between parent and child math anxiety, as well as the predicted three-way interaction between dyad type, child's math anxiety, and parent's math anxiety [$F_{(3,\ 544.56)} = 3.940$, $p = 0.048$; see **Table 4**]. The main effect of class type indicated honors math students had higher math GPAs than standard math students ($\beta = 0.415$, $p = 0.001$). The main effect of child's math anxiety indicated a negative relationship such that greater math anxiety is associated with lower math GPAs ($\beta = -0.582$, $p = 0.001$), supporting Hypothesis 1b. The two-way interaction showed a negative relationship between the interaction of parent and child math anxiety and child's math GPA. When parents' math anxiety was lower, children with lower math anxiety had higher GPAs than children with higher anxiety ($b = -0.442$, $p = 0.001$). The same relationship held for parents with moderate ($b = -0.422$, $p = 0.001$) and higher ($b = -0.402$, $p = 0.001$) math anxiety, though the slopes are slightly lower as parent anxiety increases. The three-way interaction model showed a significant relationship only for the Father-Son dyad, supporting Hypothesis 3 ($\beta = -0.457$, $p = 0.026$; see **Figure 2**). When sons had lower math anxiety, their GPAs were higher compared to sons with higher math anxiety. Interestingly this relationship was strongest when fathers' had higher math anxiety, contrary to Hypothesis 2 (GPA around 3.5; $b = -1.01$, $p = 0.005$). There was a similar pattern when father's math anxiety was moderate (GPA around 3.2; $b = -0.629$, $p = 0.008$). The relationship was not significant when father's anxiety was lower. There were no three-way interactions for other Parent-Child dyads (see Supplementary Results).

Math Behavioral Intentions

The model predicting child's math behavioral intentions indicated main effects of class type and child's math anxiety, and a two-way interaction between dyad type and child's math anxiety, [$F_{(3,\ 574.65)} = 5.370$, $p = 0.021$; see **Table 5**]. The predicted three-way interaction was not significant. The main effect of class type indicated honors math students had lower math behavioral intentions than standard math students ($\beta = -0.158$, $p = 0.049$). The main effect of child's math anxiety indicated a negative relationship such that greater math anxiety is associated with lower math behavioral intentions ($\beta = -0.319$, $p = 0.008$), supporting Hypothesis 1c. The two-way interaction model showed a marginally significant relationship only for the Mother-Daughter dyad that indicated the lower daughters' math anxiety, the higher their math behavioral intentions particularly if their mothers had lower math anxiety ($\beta = 0.251$, $p = 0.054$, see **Figure 3**), providing some support for Hypotheses 2 and 3a. However, when daughters had higher math anxiety, their math behavioral intentions were lower, particularly when mothers' math anxiety was low, contrary to Hypothesis 2. There

TABLE 3 | Correlations among continuous variables.

	1	2	3	4	5	6	7
1. Child math anxiety	–						
2. Parent math anxiety	0.500***	–					
3. Math self-efficacy	−0.415***	−0.250***	–				
4. Math GPA	−0.371***	−0.210***	0.526***	–			
5. Math intentions	−0.200***	−0.050	0.416***	0.141***	–		
6. Math attitudes	−0.409***	−0.203***	0.441***	0.241***	0.483***	–	
7. Math devaluing	0.196***	0.099*	−0.379***	−0.134***	−0.598***	−0.486***	–

*$p < 0.05$, ***$p < 0.001$.*

TABLE 4 | Three-way interaction predicting math self-efficacy and math GPA.

	Math self-efficacy			Math GPA		
	B	**SE**	***P***	***B***	***SE***	***P***
Intercept	4.751	0.185	0.001	2.126	0.282	0.001
Class type	−0.167	0.099	0.093	0.415	0.112	0.001
Grade level	−0.167	0.078	0.041	−0.201	0.145	0.178
Dyad type	0.106	0.048	0.029	−0.007	0.050	0.883
Child math anxiety	−0.472	0.156	0.003	0.582	0.160	0.001
Parent math anxiety	−0.300	0.165	0.069	−0.165	0.183	0.367
Parent × Child Math anxiety	−0.233	0.171	0.175	−0.395	0.196	0.044
Dyad type × Child math anxiety	−0.056	0.050	0.262	−0.074	0.052	0.155
Dyad type × Parent math anxiety	−0.076	0.054	0.162	−0.003	0.058	0.960
Three-way interaction	−0.140	0.049	0.005	−0.108	0.054	0.048

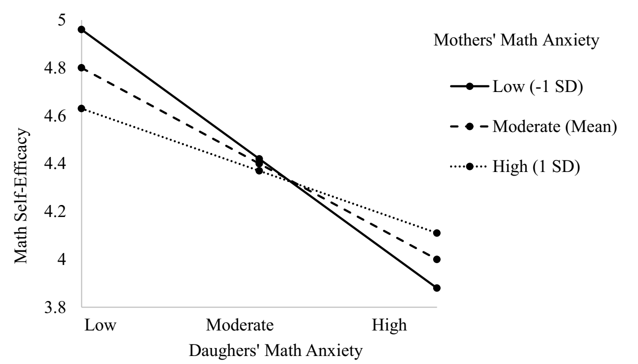

FIGURE 1 | Three-way interaction predicting math self-efficacy from Mother's and Daughter's math anxiety.

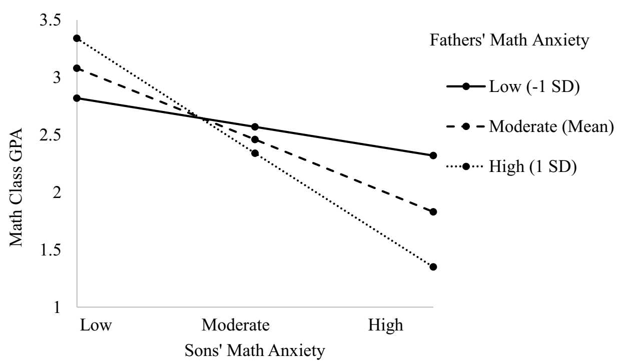

FIGURE 2 | Three-way interaction predicting math GPA from Father's and Son's math anxiety.

were no two-way interactions for other Parent-Child dyads (see Supplementary Results).

Math Attitudes

The model predicting child's math attitudes indicated main effects of grade level, dyad type, and child's math anxiety (see **Table 5**). There was a two-way interaction between parent and child math anxiety, as well as a three-way interaction between dyad type, child's math anxiety, and parent's math anxiety, [$F_{(3,\ 572.83)} = 4.580$, $p = 0.004$; see **Table 5**]. The main effect of grade level indicated math attitudes become more negative as children progress through middle school ($\beta = -0.259$, $p = 0.002$; 6th grade $M = 4.670$, $SD = 0.430$; 7th grade $M = 4.460$, $SD = 0.429$; 8th grade $M = 4.090$, $SD = 0.462$). The main effect of dyad type indicated significant differences between dyads such that son's in Father-Son dyads had significantly more positive math attitudes ($M = 4.690$, $SD = 0.530$) than sons and daughters in all other dyad types (Ms $= 4.240 - 4.470$, SDs $= 0.427$–0.510).

TABLE 5 | Interactions predicting math behavioral intentions and math attitudes.

	Math behavioral intentions			Math attitudes		
	B	***SE***	***P***	***B***	***SE***	***P***
Intercept	4.484	0.164	0.001	4.58	0.177	0.001
Class type	−0.158	0.080	0.049	−0.059	0.089	0.509
Grade level	−0.127	0.072	0.091	−0.259	0.072	0.002
Dyad type	0.061	0.037	0.097	0.195	0.042	0.001
Child math anxiety	−0.319	0.119	0.008	−0.467	0.134	0.001
Parent math anxiety	0.121	0.126	0.338	0.170	0.141	0.228
Parent × Child math anxiety	−0.021	0.131	0.870	−0.355	0.147	0.016
Dyad type × Child math anxiety	−0.088	0.038	0.021	−0.033	0.043	0.435
Dyad type × Parent math anxiety	0.032	0.042	0.438	0.054	0.047	0.247
Three-way interaction	−0.040	0.038	0.287	−0.135	0.043	0.002

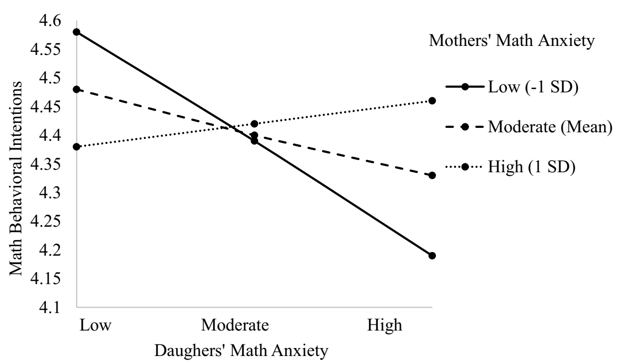

FIGURE 3 | Two-way interaction predicting math behavioral intentions from Mother's and Daughter's math anxiety.

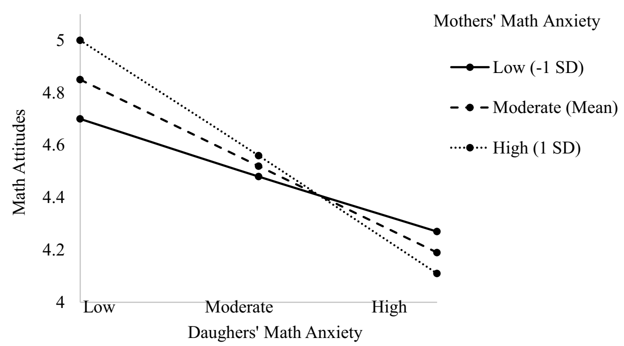

FIGURE 4 | Three-way interaction predicting math attitudes from Mothers' and Daughters' math anxiety.

This main effect is further explained by the three-way interaction and is described in more detail next. The main effect of child's math anxiety indicated a negative relationship such that greater math anxiety is associated with more negative math attitudes ($\beta = -0.467$, $p = 0.001$), consistent with Hypothesis 1d. The two-way interaction showed a negative relationship between the interaction of parent and child math anxiety and child's math attitudes ($\beta = -0.355$, $p = 0.016$). When children had lower math anxiety, their math attitudes were positive regardless of parent's math anxiety. However, when children's math anxiety was moderate to high, the higher parent's math anxiety, the lower children's math attitudes, supporting Hypothesis 2. This two-way interaction is subsumed by the three three-way interaction and is described in more detail next. The three-way interactions were significant for Mother-Daughter ($\beta = 0.453$, $p = 0.004$), Mother-Son ($\beta = -0.231$, $p = 0.005$), and the Father-Son dyad ($\beta = -0.453$, $p = 0.004$; see **Figures 4–6**). For the Mother-Daughter dyad, daughters with lower math anxiety had more positive math attitudes than daughters with higher math anxiety, and this relationship was strongest when mothers had higher anxiety ($b = -0.414$, $p = 0.001$) contrary to hypothesis 2, followed by moderate ($b = -0.339$, $p = 0.001$), followed by lower anxiety ($b = -0.264$, $p = 0.003$). For the Mother-Son dyad, sons with lower math anxiety had more positive math attitudes than sons with higher math anxiety, and this relationship was strongest when mothers had high anxiety ($b = -0.430$, $p = 0.001$) contrary to Hypothesis 2, followed by moderate ($b = -0.321$, $p = 0.001$), followed by low anxiety ($b = -0.212$, $p = 0.030$). For the Father-Son dyad, sons with lower math anxiety had more positive math attitudes than sons with higher math anxiety, and this relationship was strongest when fathers had high anxiety ($b = -0.796$, $p = 0.005$), contrary to Hypothesis 2, followed by moderate ($b = -0.494$, $p = 0.007$). This relationship was not significant when fathers had lower anxiety ($b = -0.193$, $p = 0.286$). There were no three-way interactions for other Parent-Child dyads (see Supplementary Results).

Math Devaluing

The model predicting child's math devaluing indicated main effects of grade level, dyad type, and child's math anxiety (see **Table 6**). There was a marginal three-way interaction between dyad type, child's math anxiety, and parent's math anxiety, [$F_{(3,\ 576.30)} = 2.330$; $p = 0.074$, see **Table 6**]. The main effect of grade level indicated math devaluing increases as children progress through middle school ($\beta = 0.120$, $p = 0.040$; 6th

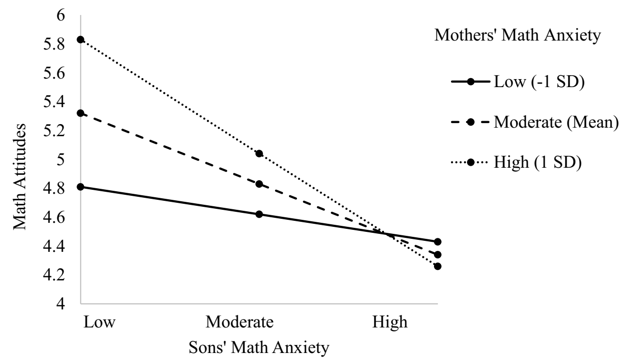

FIGURE 5 | Three-way interaction predicting math attitudes from Mothers' and Sons' math anxiety.

TABLE 6 | Three-way interaction predicting math devaluing.

	Math devaluing		
	B	***SE***	***p***
Intercept	1.846	0.146	0.001
Class type	0.003	0.079	0.968
Grade level	0.120	0.054	0.040
Dyad type	−0.099	0.039	0.011
Child math anxiety	0.253	0.125	0.043
Parent math anxiety	0.012	0.132	0.930
Parent × Child math anxiety	0.144	0.137	0.296
Dyad type × Child math anxiety	0.059	0.040	0.141
Dyad type × Parent math anxiety	−0.010	0.044	0.816
Three-way interaction	0.050	0.040	0.074

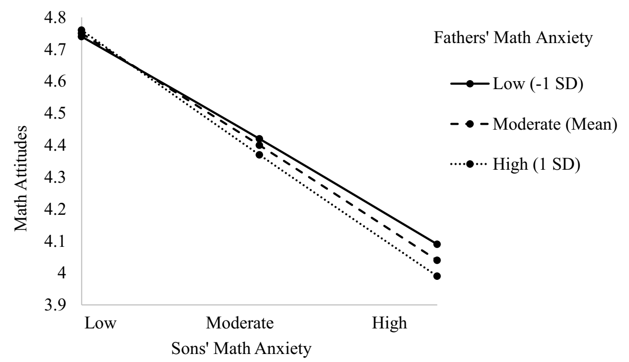

FIGURE 6 | Three-way interaction predicting math attitudes from Fathers' and Sons' math anxiety.

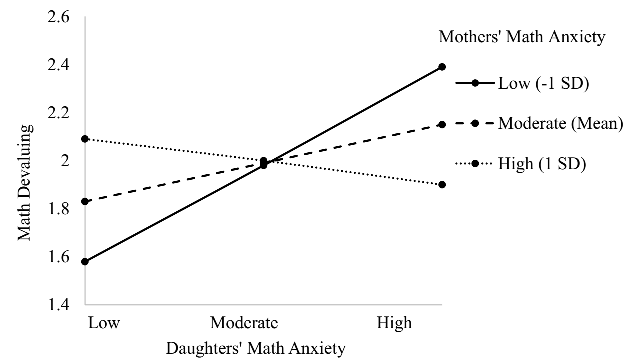

FIGURE 7 | Three-way interaction predicting math devaluing from Mothers' and Daughters' math anxiety.

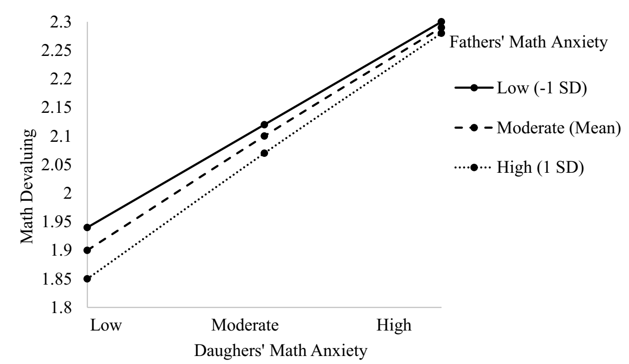

FIGURE 8 | Three-way interaction predicting math devaluing from Fathers' and Daughters' math anxiety.

grade $M = 1.880$, $SD = 0.224$; 7th grade $M = 2.040$, $SD = 0.220$; 8th grade $M = 2.150$, $SD = 0.206$). The main effect of dyad type ($\beta = -0.099$, $p = 0.011$) indicated significant differences between dyads such that children in mother dyads had significantly more math devaluing (M-D: $M = 2.070$, $SD = 0.184$; M-S: $M = 2.110$, $SD = 0.210$), consistent with Hypothesis 3b, than children in father dyads (F-D: $M = 1.880$, $SD = 0.314$; F-S: $M = 1.830$, $SD = 0.284$). This main effect is further explained next by the marginal three-way interaction. The main effect of child's math anxiety indicated a positive relationship such that greater math anxiety is associated with more math devaluing ($\beta = 0.253$, $p = 0.043$), supporting Hypothesis 1e. The marginal three-way interaction showed that in the Mother-Daughter dyad, daughters with lower anxiety with mothers also lower in anxiety had less math devaluing than daughters with higher anxiety ($b = 0.172$, $p = 0.015$), providing some support for Hypothesis 2. However, daughters with higher math anxiety had greater math devaluing, particularly when mothers had lower math anxiety, contrary to Hypothesis 2. The relationship between daughters' anxiety and mothers' with moderate or high anxiety was not significant. The greater daughters' math anxiety, the more they devalued math; see **Figures 7**, **8**). For the Father-Daughter dyad, fathers with lower math anxiety with daughters also low in anxiety had less math devaluing than daughters higher in anxiety ($b = 0.429$, $p = 0.008$), supporting Hypothesis 2b. The relationship between daughters' anxiety and fathers with moderate or high anxiety was not significant. The greater daughters' math anxiety, the more they devalued math. There were no three-way interactions for other Parent-Child dyads (see Supplementary Results).

A summary of all the Study 1 three-way interaction results are summarized in **Tables 7**, **8**.

Discussion

The results generally support the prediction that parents' anxiety plays a role in children's math anxiety and the variables interact to predict several math education outcomes including math self-efficacy, math GPA, math behavioral intentions, math attitudes, and math devaluing. First, consistent with existing literature, there were five main effects (Hypotheses 1a–e) of child's math anxiety on all outcomes such that greater math anxiety was associated with lower math self-efficacy, lower math GPA, lower math behavioral intentions, more negative math attitudes, and greater math discounting. However, more interesting is the interaction of children's math anxiety with parents' math anxiety within gendered dyads. In support of Hypothesis 3, the same-gender parent-child dyads showed the most significant relationships, and more specifically in line with Hypothesis 3a, the Mother-Daughter dyad dominated the findings. The Mother-Daughter dyads' math anxiety predicted math self-efficacy, math behavioral intentions, math attitudes, and math devaluing, or four of the five hypothesized effects. The general pattern was consistent with the hypothesis that when both mothers' and daughters' math anxiety were low, daughters had more positive math outcomes compared to when mothers' and daughters' math anxiety were both high. For the cases when both mothers' and daughters' math anxiety were high, daughters had more negative math outcomes compared to when mothers' and daughters' math anxiety were both low for math attitudes. However, the simple effects for math self-efficacy, behavioral intentions, and math devaluing were contrary to Hypothesis 2 when daughters' math anxiety was high. In these cases, math outcomes were worst when mothers has lower math anxiety rather than higher math anxiety. A possible explanation is that mothers' involvement in

TABLE 7 | Patterns of simple effects in significant three-way interactions for math self-efficacy and math GPA.

Dyad type	Math self-efficacy				Math GPA			
		H Par	M Par	L Par				
Mother-Daughter	H Chld	Lower	Lower	*Lower	ns			
	L Chld	Higher	Higher	*Higher				
Mother-Son	ns				ns			
Father-Daughter	ns				ns			
Father-Son	ns					H Par	M Par	L Par
					H Chld	*Lower	*Lower	ns
					L Chld	*Higher	*Higher	ns

*H, High; M, Moderate; L, Low; Par, Parent; Chld, Child. Moderate is excluded for the child data because it reflects the mean and is more informative in graphic form. *Reflects the stronger relationship in the interaction.*

TABLE 8 | Patterns of simple effects in significant three-way interactions for math attitudes and math devaluing.

Dyad type	Math attitudes				Math devaluing			
		H Par	M Par	L Par		H Par	M Par	L Par
Mother-Daughter	H Chld	Lower*	Lower	Lower	H Chld	ns	ns	*Higher
	L Chld	Higher*	Higher	Higher	L Chld	ns	ns	*Lower
Mother-Son		H Par	M Par	L Par	ns			
	H Chld	Lower*	Lower	Lower				
	L Chld	Higher*	Higher	Higher				
Father-Daughter	ns					H Par	M Par	L Par
					H Chld	ns	ns	*Higher
					L Chld	ns	ns	*Lower
Father-Son		H Par	M Par	L Par	ns			
	H Chld	Lower*	Lower	Lower				
	L Chld	Higher*	Higher	Higher				

*H, High; M, Moderate; L, Low; Par, Parent; Chld, Child. Moderate is excluded for the child data because it reflects the mean and is more informative in graphic form. *Reflects the stronger relationship in the interaction.*

daughters' math education, e.g., helping with homework, may moderate these unexpected findings (see Maloney et al., 2015). It seems that daughters' level of math anxiety was a better predictor of math self-efficacy, behavioral intentions, and math devaluing such that if daughters' math anxiety was high, math outcomes were negative even when mothers' math anxiety was lower. Perhaps the sample is mixed with mothers who are more active in helping their daughters with homework and others who are less active. This moderating variable may help explain the mixed results and should be measured in future studies that examine effects of gendered parent-child dyads.

The other same-gender parent-child dyad Father-Son showed two significant effects of the five possible. Interestingly, the Father-Son dyad was the only one to show a significant relationship to GPA. When both fathers and sons had lower math anxiety, math GPA was higher. Fortunately, even when fathers' math anxiety was higher, if sons had lower math anxiety, GPA was higher. Only when both fathers and sons had higher math anxiety was GPA lower.

Consistent with predictions there not many effects for mixed-gender parent-child dyads. For the Father-Daughter dyad, fathers with lower math anxiety with daughters also low in anxiety had less math devaluing than daughters higher in anxiety. For the Mother-Son dyad, sons with lower math anxiety had more positive math attitudes than sons with higher math anxiety, and this relationship was strongest when mothers had high anxiety. This is contrary to hypotheses and suggests that sons are showing reactance against mothers' higher math anxiety. Alternatively, this might suggest that transmission of parents' anxiety might not occur to the same extent in mixed-gender dyads. Also, mothers' involvement in sons' math education (e.g., math homework) may be a moderator. Further research is needed to investigate these gendered patterns.

In sum, this study contributes to the existing literature by helping to address several gaps. First, there is only one known published study that found effects of parents' math anxiety on children's math education outcomes, particularly their math performance. Second, this study examined these relationships using a gendered lens and found support for the gender stereotype literature that the transmission of math anxiety seems most prevalent among same-gender parent-child dyads, particular the Mother-Daughter dyad.

Since math anxiety is well-established as a correlate of many important math education outcomes, Study 2 sought to examine a second source of math anxiety, math-gender stereotypes. In addition, study 2 examines math anxiety as a potential mediator explaining the relationship between endorsement of math-gender stereotypes and math achievement.

STUDY 2

The purpose of study 2 is two-fold: first to address a call for examination of antecedents of math anxiety (Ashcraft and Ridley, 2005; Jameson, 2014; Maloney et al., 2015) and second to address the call for a more mechanistic approach to examine mediators in the math anxiety and achievement domains (Gunderson et al., 2012).

Gender Stereotypes as a Source of Math Anxiety

The Expectancy-Value Theory of achievement motivation describes the role of cultural and social factors that influence children's motivations, task values, expectations for success, and achievement related choices. In regards to mathematics achievement, the cultural milieu includes cultural stereotypes about math and gender roles appropriate in the math domain (Cheryan, 2012). Children are influenced by these cultural factors and also have their own perceptions of society's stereotypes about gender and math.

A great deal of the research using an expectancy-value framework work focuses on the transmission of math-gender stereotypes from parents to children and how stereotypes influence children's achievement outcomes. A logical extension of this work is that children's own endorsement of math-gender related stereotypes will affect their achievement outcomes. Indeed, research on stereotype threat shows that women who endorse stereotypes about women's inferiority in math are more susceptible to experiencing stereotype threat and subsequently show math performance decrements (Schmader et al., 2004). Anxiety is one mechanism through which stereotype threat negatively affects performance (Schmader et al., 2008). Stereotype threat is the fear of confirming a negative stereotype about one's social group (e.g., gender), and is particularly relevant in evaluative contexts (Steele and Aronson, 1995). Like math anxiety, stereotype threat also disrupts working memory capacity and depletes necessary cognitive resources to tackle complex problems (Schmader et al., 2008).

Taken together, the work on the expectancy-value model showing that parents' and teachers' gender stereotypes influence girls' math gender stereotypes, and work in stereotype threat showing stereotypes create anxiety that negatively impacts performance, the prediction of math-related gender stereotypes as a source of math anxiety seems logical.

Work by Beilock et al. (2010) found that math-anxious female teachers reinforced math-gender stereotypes and girls' endorsement of math-gender stereotypes mediated the effect of teacher anxiety on their math performance. Thus, teachers' anxiety affects gender math stereotypes not female students' anxiety, suggesting it works indirectly through stereotypes.

This finding provides further evidence that math-gender stereotypes can create math anxiety in girls.

Math Anxiety as a Mechanism

Existing research on the negative effects of math anxiety suggests that it can function as a mechanism influencing math achievement. Studies have found that math anxiety lowers math performance regardless of actual math ability (Hembree, 1990; Maloney and Beilock, 2012; Park et al., 2014). Research by Chipman et al. (1992) found that math anxiety was a mediator in students' career choice. As Gunderson et al. (2012) stated, children's stereotypes, self-perceptions, math anxieties, and math achievement are all interconnected, therefore it is critical to know which component of children's gendered math attitudes is affected by specific behaviors from parents or teachers. One way to address this question is to test math-gender stereotypes as a predictor of math anxiety.

Hypotheses

In Study 2 we argue that in addition to parents, math-related gender stereotypes are a source of math anxiety. We base this argument on research showing that math-gender stereotypes held by parents, teachers, and important others are linked to reports of higher math anxiety by females more so than males (Hembree, 1990). Further, students' endorsement of math-gender stereotypes mediated the effect of teacher anxiety on their math performance (Beilock et al., 2010). Additionally, we predict that math anxiety is a mechanism through which math-gender stereotypes negatively influence math outcomes for *both* girls and boys. Specifically we predict that (1) endorsement of math-gender stereotypes will predict math anxiety such that greater endorsement is associated with greater anxiety. Although we expect the variables to be correlated, and therefore bidirectional, we expect that (2) stereotypes are a stronger predictor of anxiety than vice versa. Further we predict that endorsement of math-gender stereotypes will be negatively related to (3a) math self-efficacy, (3b) math GPA, (3c) math behavioral intentions, (3d) math attitudes, (3e) and positively related to math devaluing. Finally, we predict that (4) math anxiety will fully mediate the relationship between math-gender stereotype endorsement and math outcomes. Although much of the focus on math-gender stereotypes has been on girls and women, (5) we predict these same relationships for boys, although the effects will be larger for girls. Boys who endorse math-gender stereotypes believe that boys and men *are* (descriptive stereotype) and *should be* (injunctive stereotype) superior to women in math. However, societal stereotypes of high math achievement reflects majority group members (Stephens et al., 2012), specifically males, Caucasians but also Asian Americans (Shih et al., 1999), and middle to upper middle class educated males. Not all males "benefit" from gender stereotypes about men's superiority math as we see in research on stereotype lift (Walton and Cohen, 2003). In our sample of racially diverse, low-income students, endorsing such stereotypes is likely to be threatening and remind male participants that they may not be high achieving in the math domain (Croizet and Claire, 1998).

Method

Participants

The sample included 1342 students ($n = 713$, 53% female; $n = 629$, 47% male) from the same project described in Study 1; however, the sample included all students who completed a questionnaire in the classroom, regardless of whether their parent participated in the study. Students came from the same 8 schools in southern California and were enrolled in 6th grade ($n = 361$), 7th grade ($n = 459$), or 8th grade ($n = 522$) honors ($n = 768$), or standard ($n = 574$) math classes with one of 24 teachers. Students self-reported their race/ethnicity and the largest group represented was Latino/a or Hispanic ($n = 910$, 68%) followed by 131 (10%) multiracial, 111 (8%) Asian/Pacific Islander, and less than 5% each of remaining groups including Native American, White/Caucasian, and Other. Nearly 5% of students ($n = 63$) did not report a race or ethnicity. Students' ages ranged from 11 to 14 reflecting ages in the 6th through 8th grades.

Materials

Participants completed a 9-item measure of endorsement of math-related gender stereotypes on a scale from 1 (*Very Strongly Disagree*) to 6 (*Very Strongly Agree*). Sample items included "Girls are worse at math than boys," "Girls are better at English, art, and history than math," "Girls can do just as well as boys in math" (reverse-scored) and "Girls who like studying math are nerds." The items had acceptable internal consistency ($\alpha = 0.803$) and were reverse scored and averaged so that higher values represented more endorsement of math-related gender stereotypes.

Participants' math anxiety was assessed with the same measure from study 1. The items had acceptable internal consistency ($\alpha = 0.727$) for this sample and were averaged so that higher values represented greater anxiety.

Participants' math self-efficacy was measured by the same 5-item measure reported in Study 1. The scale was internally consistent for this sample ($\alpha = 0.881$) and items were averaged so that higher values represented greater math self-efficacy.

Participants' math education behavioral intentions were measured by the 6 items used in study 1. The items were reliable for this sample ($\alpha = 0.753$) and items were averaged so that higher values represented greater math intentions.

Math attitudes were measure by the 5-item scale from study 1. The measure was reliable ($\alpha = 0.760$) and averaged so that higher values indicated more positive attitudes.

Finally, participants' math devaluing was assessed by the 5 items used in study 1. The scale was internally consistent for this sample ($\alpha = 0.793$) and items were averaged so that higher values represented greater math devaluing.

Procedure

The procedure was identical to Study 1. Participants completed the questionnaire during the assigned class time, which took 20–30 min, and the questionnaire was offered in both English and Spanish. The researchers collected the questionnaires and obtained the math class GPA roster from the teachers.

Analysis Strategy

Like Study 1, the data came from an inherently hierarchical structure of children (Level 1) nested within classrooms with different teachers (Level 2). Multilevel modeling (MLM; Raudenbush and Bryk, 2002) was used to analyze the nested data, in this case in which the focal variables of interest are all situated on one level. Two-level random intercept models were computed using the restricted maximum likelihood estimation, which adjusts for unequal sample sizes and is ideal for smaller datasets, with variance components estimator in SPSS Mixed Models Version 21 (IBM Corp., 2012). Mediation analyses were conducted following guidelines by Baron and Kenny (1986) within a MLM framework to account for the nested data. Path A tested the relationship between the predictor variable (gender stereotypes) and the mediator (math anxiety), path B tested the relationship between the mediator and the outcome variable (math self-efficacy, math GPA, math intentions, math attitudes, and math devaluing), and path C tested the relationship between the predictor variable and the outcome variable. To test the significance of C' we computed the path from the predictor to the outcome variable while controlling for the mediator. In cases of significant mediation, reverse mediation will be tested and a Sobel test will be used to determine significant differences in the size of beta values. To examine gender differences and similarities in the mediation models, models will be run separately by gender. Consistent with Study 1, in all models we controlled for grade level and math class type.

Results

For descriptive purposes, the means, standard deviations, and correlations for all study variables are provided in **Table 9**. All correlations are significant, except for one, and in the predicted direction, supporting Hypotheses 1 and 3a–e. There is a positive relationship between endorsement of math-gender stereotypes and math anxiety for both girls and boys. There is a negative relationship between math-gender stereotypes and math self-efficacy, math intentions, and math attitudes for both girls and boys and a negative relationship between math-gender stereotypes and math GPA for girls only. There is a marginal trend for boys, but it did not reach significance at the 0.05 level for a two-tailed test ($p = 0.076$). Math-gender stereotypes were positively correlated with math devaluing for both girls and boys. Math anxiety was negatively correlated with math self-efficacy, math GPA, math intentions, and math attitudes, and positively correlated with math devaluing for both girls and boys. Math self-efficacy was positively related to math GPA, math intentions, and math attitudes, and negatively related to math devaluing for both girls and boys. Math GPA was positively related to math intentions and attitudes, and negatively related to math devaluing for both girls and boys. Math intentions and math attitudes were positively related and both were negatively related to math devaluing for both gender groups.

Mediational Models for Girls

Math self-efficacy

The mediational models supported Hypothesis 4 that math anxiety mediates the effect of math-gender stereotypes on math self-efficacy, and the size of these relationship did not differ by gender, counter to Hypothesis 5. In support of the mediation models for girls, the more girls endorsed math-gender stereotypes, the greater their math anxiety ($\beta = 0.257$, $p = 0.001$; Path A, see **Table 10A**). Math anxiety was negatively related to math self-efficacy such that greater math anxiety predicted lower math self-efficacy ($\beta = -0.382$, $p = 0.001$; Path B, see **Table 10B**). The direct effect of math-gender stereotypes on math self-efficacy was negative, such that greater endorsement of stereotypes predicted lower math self-efficacy ($\beta = -0.125$, $p = 0.024$; Path C, see **Table 10B**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math self-efficacy was no longer significant (Path C', see **Table 10B**). Thus, math anxiety is a mediator of the relationship between math-gender stereotypes and math self-efficacy, supporting Hypothesis 4. Since the data are correlational and cross-sectional, a reverse mediation analysis was computed to rule out math-gender stereotypes as a mediator, particularly because the variables are correlated, $r_{(696)} = 0.191$, $p = 0.001$. The reverse mediation model showed the same pattern of relationships for math anxiety predicting gender stereotypes, although it was weaker ($\beta = 0.133$, $p = 0.001$). A sobel test confirmed that the beta for math-gender stereotypes predicting anxiety ($\beta = 0.257$) was significantly greater than the beta for anxiety predicting stereotypes ($\beta = 0.133$), $z = 2.120$, $p = 0.034$, supporting Hypothesis 2. Math-gender stereotypes also predicted self-efficacy ($\beta = -0.123$, $p = 0.026$), which was also weaker than the standard mediational model, z = 3.910, $p = 0.001$. However, when math-gender stereotypes was entered as the mediator, the direct relationship between math anxiety and self-efficacy did not change (C path $\beta = -0.382$, $p = 0.001$; C' path $\beta = -0.381$, $p = 0.001$), indicating math-gender stereotypes does not mediate the relationship between math anxiety and math self-efficacy, supporting Hypothesis 4.

Math GPA

The mediational models support Hypothesis 4 that math anxiety mediates the effect of math gender stereotypes on math GPA, and that the size of these relationship differs by gender, supporting Hypothesis 5. In support of the mediation models for girls, math anxiety was negatively related to math GPA such that greater math anxiety predicted lower math GPA ($\beta = -0.325$, $p = 0.001$; Path B, see **Table 10B**). The direct effect of gender stereotypes on math GPA was negative, such that greater endorsement of math-gender stereotypes predicted lower math GPA ($\beta = -0.137$, $p = 0.012$; Path C, see **Table 10B**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math GPA was no longer significant. Thus, math anxiety is a mediator for the relationship between math-gender stereotypes and math GPA. The same reverse mediation analysis was conducted and indicated the direct effect of anxiety on math GPA did not significantly change when math-gender stereotypes was added to the model, thus math anxiety is the mediator rather than math-gender stereotypes.

Math intentions

The mediational models testing math anxiety as a mediator of the effect of math-gender stereotypes on math intentions was not significant, contrary to Hypothesis 4; however the pattern of relationships were in the predicted directions (see **Table 11A**). For girls, math anxiety was negatively related to math intentions such that greater math anxiety predicted lower math intentions ($\beta = -0.108$, $p = 0.001$; Path B, see **Table 11B**). The direct effect of math-gender stereotypes on math intentions was negative, such that greater endorsement of stereotypes predicted lower math intentions ($\beta = -0.205$, $p = 0.012$; Path C, see **Table 11B**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math intentions was weaker ($\beta = -0.187$, $p = 0.001$; Path C', see **Table 11B**), but the difference was not statistically significant, z = 0.322, $p > 0.05$. This indicates that math anxiety does not mediate the relationship between math-gender stereotypes and math intentions.

TABLE 9 | Descriptive statistics and correlation matrix by gender for all variables.

	M	*SD*	1	2	3	4	5	6	7
1. Gender stereotypes	2.318	0.756	–	0.191***	−0.086*	−0.116**	−0.193***	−0.252***	0.287***
	2.567	0.861							
2. Math anxiety	3.051	1.068	0.180***	–	−0.365***	−0.385***	−0.154***	−0.367***	0.133***
	2.800	1.048							
3. Math self-efficacy	4.469	1.107	−0.106**	−0.351***	–	0.520***	0.369***	0.392***	−0.350***
	4.436	1.163							
4. Math GPA	2.369	1.156	−0.074^	−0.372***	0.550***	–	0.142***	0.231***	−0.183***
	2.088	1.228							
5. Math. intentions	4.511	0.808	−0.088*	−0.167***	0.440***	0.169***	–	0.504***	−0.584***
	4.381	0.829							
6. Matk attitudes	4.356	0.950	−0.156***	−0.336***	0.475***	0.305***	0.591***	–	−0.496***
	4.419	1.00							
7. Math devaluing	2.025	0.843	0.176***	0.182***	−0.383***	−0.157***	−0.626***	−0.594***	–
	2.089	0.891							

*Girls' values, are above the diagonal in bold and boys' values are below the diagonal in standard typeface.^p = 0.076, *p < 0.05, **p < 0.01, ***p < 0.001.*

TABLE 10 | Mediation model statistics for girls' math self-efficacy arid math GPA.

A	Outcome: Math anxiety (M)			
Antecedent	**Identifier**	**Coeff**	***SE***	***P***
Intercept	i_1	2.650	0.180	0.001
Grade level	Control	0.184	0.080	0.029
Class type	Control	−0.059	0.096	0.542
Math Anxiety (M)	–	–	–	–
Gender Stereotypes (X)	A	0.257	0.052	0.001
Model Summary	$F_{(1,\ 692)} = 24.289, p = 0.001$			

B	Outcome: Math Self-Efficacy (Y)				Outcome: Math GPA (Y)			
Antecedent	**Identifier**	**Coeff**	***SE***	***P***	**Identifier**	**Coeff**	***SE***	***P***
Intercept	i_2	5.734	0.199	0.001	i_2	3.400	0.278	0.001
Grade level	Control	−0.032	0.073	0.680	Control	−0.102	0.145	0.488
Class type	Control	−0.127	0.095	0.182	Control	0.320	0.097	0.001
Math Anxiety (M)	b	−0.382	0.037	0.001	b	−0.325	0.096	0.001
Gender Stereotypes (X)	c	−0.125	0.055	0.024	c	−0.137	0.055	0.012
	c′	−0.034	0.053	0.524	c′	−0.043	0.052	0.406
Model summary	$F_{(1,\ 690)} = 101.69, p = 0.001$				$F_{(1,\ 639)} = 106.60, p = 0.001$			

Math attitudes

The mediational models testing math anxiety as a mediator of the effect of math-gender stereotypes on math attitudes was not significant, contrary to Hypothesis 4; however, the pattern of relationships were in the predicted directions. For girls, math anxiety was negatively related to math attitudes such that greater math anxiety predicted lower math attitudes ($\beta = -0.309$, $p = 0.001$; Path B, see **Table 11B**). The direct effect of math-gender stereotypes on math attitudes was negative, such that greater endorsement of stereotypes predicted lower math attitudes ($\beta = -0.314$, $p = 0.001$; Path C, see **Table 11B**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math attitudes was weaker ($\beta = -0.248$, $p = 0.001$; Path C', see **Table 11B**), but the difference was not statistically significant, $z = 1.049$, $p > 0.05$. This indicates that math anxiety does not mediate the relationship between math-gender stereotypes and math attitudes.

Math devaluing

The mediational models testing math anxiety as a mediator of the effect of math-gender stereotypes on math devaluing was not significant, contrary to Hypothesis 4; however the pattern

TABLE 11 | Mediation model statistics for girls' math intentions, attitudes, and devaluing.

A	Outcome: Math Anxiety (M)			
Antecedent	**Identifier**	**Coeff**	***SE***	***P***
Intercept	i_1	2.650	0.180	0.001
Grade level	Control	0.184	0.080	0.029
Class type	Control	−0.059	0.096	0.542
Math anxiety (M)	–	–	–	–
Gender stereotypes (X)	a	0.257	0.052	0.001
Model summary	$F_{(1, 692)} = 24.289, p = 0.001$			

B	Outcome: Math intentions (Y)				Outcome: Math Attitudes (Y)			
Antecedent	**Identifier**	**Coeff**	**SE**	***p***	**Identifier**	**Coeff**	**SE**	***P***
Intercept	i_2	4.760	0.132	0.001	i_2	5.119	0.145	0.001
Grade level	Control	0.164	0.116	0.178	Control	−0.161	0.062	0.015
Class type	Control	−0.035	0.073	0.630	Control	0.021	0.080	0.794
Math anxiety (M)	b	−0.108	0.028	0.001	b	−0.309	0.031	0.001
Gender stereotypes (X)	c	−0.205	0.039	0.001	c	−0.314	0.045	0.001
	c'	−0.187	0.040	0.001	c'	−0.248	0.044	0.001
Model summary	$F_{(1, 689)} = 8.857, p = 0.001$				$F_{(1, 691)} = 33.651, p = 0.001$			

C	Outcome: Math Devaluing (Y)			
Antecedent	**Identifier**	**Coeff**	***SE***	***p***
Intercept	i_2	0.826	0.377	0.043
Grade level	control	0.131	0.054	0.029
Class type	control	−0.052	0.074	0.478
Math anxiety (M)	b	0.098	0.030	0.001
Gender stereotypes (X)	c	0.322	0.040	0.001
	c′	0.313	0.041	0.001
Model summary	$F_{(1, 691)} = 15.967, p = 0.001$			

of relationships were in the predicted directions. For girls, math anxiety was positively related to math devaluing such that greater math anxiety predicted greater math devaluing ($\beta = 0.098$, $p = 0.001$; Path B, see **Table 11C**). The direct effect of math-gender stereotypes on math devaluing was positive, such that greater endorsement of stereotypes predicted greater math devaluing ($\beta = 0.322$, $p = 0.001$; Path C, see **Table 11C**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math devaluing was weaker ($\beta = 0.313$, $p = 0.001$; Path C', see **Table 11C**), but the difference was not statistically significant, $z = 0.122$, $p > 0.05$. This indicates that math anxiety does not mediate the relationship between math-gender stereotypes and math devaluing.

Mediational Models for Boys

Math self-efficacy

In support of Hypothesis 4, the mediational model for math self-efficacy was significant. In support of the mediation models for boys, the more boys endorsed math-gender stereotypes, the greater their math anxiety ($\beta = 0.214$, $p = 0.001$; Path A, see **Table 12A**). Math anxiety was negatively related to math self-efficacy such that greater math anxiety predicted lower math self-efficacy ($\beta = -0.383$, $p = 0.001$; Path B, see **Table 12B**). The direct effect of math-gender stereotypes on math self-efficacy was negative, such that greater endorsement of stereotypes predicted lower math self-efficacy ($\beta = -0.128$, $p = 0.017$; Path C, see **Table 12B**). However, when math anxiety was entered into the model the effect of math-gender stereotypes on math self-efficacy was no longer significant. Thus, math anxiety is a mediator of the relationship between math-gender stereotypes and math self-efficacy. Reverse mediation was not significant, indicating math-gender stereotypes is not a mediator of the relationship between math anxiety and math self-efficacy.

Math GPA

In partial support of Hypothesis 4, there was an indirect effect of math-gender stereotypes on math GPA; however, the mediational model was not significant due to the marginal trend between

TABLE 12 | Mediation model statistics for boys' math self-efficacy and Math GPA.

A	**Outcome: Math anxiety (M)**			
Antecedent	**Identifier**	**Coeff**	**SE**	***p***
Intercept	i_1	2.283	0.185	0.001
Grade level	control	−0.010	0.086	0.912
Class type	control	−0.070	0.099	0.477
Math anxiety (M)	–	–	–	–
Gender stereotypes (X)	A	0.214	0.048	0.001
Model summary	$F_{(1,\ 613)} = 19.861, p = 0.001$			

B	**Outcome: Math self-efficacy (Y)**				**Outcome: Math GPA (Y)**			
Antecedent	**Identifier**	**Coeff**	***SE***	***P***	**Identifier**	**Coeff**	***SE***	***p***
Intercept	i_2	5.518	0.222	0.001	i_2	3.05	0.261	0.001
Grade level	Control	−0.184	0.010	0.081	Control	−0.230	0.129	0.089
Class type	Control	−0.118	0.105	0.258	Control	0.244	0.108	0.023
Math anxiety (M)	b	−0.383	0.041	0.001	b	−0.405	0.043	0.001
Gender stereotypes (X)	c	−0.128	0.054	0.017	c	−0.092	0.056	0.101
	c′	−0.051	0.051	0.323	c′	−0.006	0.053	0.910
Model summary	$F_{(1,\ 612)} = 74.888, p = 0.001$				$F_{(1,\ 564)} = 80.958, p = 0.001$			

math-gender stereotypes and math GPA for boys. The model paths showed the same pattern, that math-gender stereotypes was positively related to math anxiety, and math anxiety was negatively related to math GPA such that greater math anxiety predicted lower math GPA ($\beta = -0.405$, $p = 0.001$; Path B, see **Table 12B**). The direct effect of math-gender stereotypes on math GPA was negative but marginal ($\beta = -0.092$, $p = 0.101$); however, accounting for math anxiety reduced this effect substantially ($\beta = -0.006$, $p = 0.91$; Path C, see **Table 12B**), indicating an indirect effect of gender stereotypes. A reverse mediation model is not plausible given the lack of a significant direct relationship between math-gender stereotypes and math GPA for boys. Since the mediational model for girls was significant but not for boys, this provides support for Hypothesis 5 that the size of the relationship differs by gender.

Math intentions

Contrary to Hypothesis 4, the mediational model for math intentions was not significant; however the pattern of relationships were in the predicted directions (see **Table 13A**). Math anxiety was negatively related to math intentions such that greater math anxiety predicted lower math intentions ($\beta = -0.148$, $p = 0.001$; Path B, see **Table 13B**). The direct effect of math-gender stereotypes on math intentions was negative, such that greater endorsement of stereotypes predicted lower math intentions ($\beta = -0.096$, $p = 0.017$; Path C, see **Table 13B**). When math anxiety was entered into the model the effect of math-gender stereotypes on math intentions remained significant ($\beta = -0.082$, $p = 0.040$; Path C', see **Table 13B**) and the reduction in the beta value was not significant, z = 0.0247, $p > 0.05$. Thus, math anxiety is a not a mediator of the relationship between math-gender stereotypes and math intentions.

Math attitudes

Contrary to Hypothesis 4, the mediational model for math attitudes was not significant; however the pattern of relationships were in the predicted directions. Math anxiety was negatively related to math attitudes such that greater math anxiety predicted lower math attitudes ($\beta = -0.325$, $p = 0.001$; Path B, see **Table 13B**). The direct effect of math-gender stereotypes on math attitudes was negative, such that greater endorsement of stereotypes predicted more negative math attitudes ($\beta = -0.191$, $p = 0.007$; Path C, see **Table 13B**). When math anxiety was entered into the model the effect of math-gender stereotypes on math attitudes remained significant ($\beta = -0.134$, $p = 0.002$; Path C', see **Table 13B**) and the reduction in the beta value was not significant, z = 0.895, $p > 0.05$. Thus, math anxiety is a not a mediator of the relationship between math-gender stereotypes and math attitudes.

Math devaluing

Contrary to Hypothesis 4, the mediational model for math devaluing was not significant; however the pattern of relationships were in the predicted directions. Math anxiety was positively related to math devaluing such that greater math anxiety predicted greater math devaluing ($\beta = 0.165$, $p = 0.001$; Path B, see **Table 13C**). The direct effect of math-gender stereotypes on math devaluing was positive, such that greater endorsement of stereotypes predicted greater math devaluing ($\beta = 0.1731$, $p = 0.001$; Path C, see **Table 13C**). When math anxiety was entered into the model the effect of math-gender

TABLE 13 | Mediation model statistics for boys' math intentions, attitudes, and devaluing.

A	Outcome: Math anxiety (M)			
Antecedent	Identifier	Coeff	*SE*	*p*
Intercept	i_1	2.283	0.185	0.001
Grade level	Control	−0.010	0.086	0.912
Class type	Control	−0.070	0.099	0.477
Math anxiety (M)	–	–	–	–
Gender stereotypes (X)	a	0.214	0.048	0.001
Model summary	$F_{(1, 613)} = 19.861, p = 0.001$			

B	Outcome: Math intentions (Y)				Outcome: Math attitudes (Y)			
Antecedent	Identifier	Coeff	*SE*	*p*	Identifier	Coeff	*SE*	*p*
Intercept	i_2	5.87	0.499	0.001	i_2	6.73	0.475	0.001
Grade level	Control	−0.131	0.071	0.081	Control	−0.195	0.067	0.011
Class type	Control	−0.176	0.078	0.024	Control	−0.038	0.085	0.658
Math anxiety (M)	b	−0.148	0.031	0.001	b	−0.325	0.036	0.001
Gender stereotypes (X)	c	−0.096	0.040	0.017	c	−0.191	0.046	0.001
	c′	−0.082	0.040	0.040	c′	−0.134	0.044	0.002
Model summary	$F_{(1, 607)} = 8.818, p = 0.001$				$F_{(1, 612)} = 20.241, p = 0.001$			

C	Outcome: Math devaluing (Y)			
Antecedent	Identifier	Coeff	*SE*	*p*
Intercept	i_2	0.653	0.571	0.267
Grade level	Control	0.142	0.081	0.096
Class type	Control	0.032	0.083	0.703
Math anxiety (M)	b	0.165	0.034	0.001
Gender stereotypes (X)	C	0.173	0.041	0.001
	c′	0.140	0.041	0.001
Model summary	$F_{(1, 612)} = 8.657, p = 0.001$			

stereotypes on math devaluing remained significant (β = 0.140, $p = 0.001$; Path C', see **Table 13C**) and the reduction in the beta value was not significant, z = 0.569, $p > 0.05$. Thus, math anxiety is a not a mediator of the relationship between math-gender stereotypes and math devaluing.

Discussion

Results from Study 2 supported the hypotheses that endorsement of math-gender stereotypes was negatively related to two math outcomes including math self-efficacy and math GPA for both girls and boys. Math anxiety fully mediated the relationship between endorsement of math-gender stereotypes and math self-efficacy and math GPA. Thus, the persistence of math-based gender stereotypes in the US are not only inaccurate, but they are harmful for both girls' and boys' math achievement.

Results support the argument that endorsement of math-gender stereotypes may serve as an antecedent to math anxiety. Although the variables are correlated, regression analyses indicate the stronger relationship is from stereotypes to anxiety for two math outcomes: self-efficacy for girls and boys, and math GPA for girls. Further, mediational analyses indicate that math anxiety, not math gender stereotypes, mediate the relationship between endorsement of math-gender stereotypes and negative math achievement. Interestingly, although the predicted patterns of relationships emerged, math anxiety did not mediate the relationship between math-gender stereotypes and math attitudes, intentions, or devaluing. It may be that gender stereotypes have a stronger relationship with more achievement outcomes (e.g., self-efficacy and GPA) and math anxiety serves as a mediator of these relationships, but not for more attitudinal variables. Future research is needed to better understand the conditions under which math anxiety serves as a mediator between math-gender stereotypes and math outcomes.

This study provided initial evidence that the socialization of, and endorsement of math-gender stereotypes among girls and boys is related to negative math achievement. Further, math anxiety serves as a mechanism for lower math self-efficacy and math performance but not math attitude related variables.

GENERAL DISCUSSION

The purpose of this research was to further probe the social determinants of adolescents' math anxiety by examining the relationship between same and other-gender parents' math anxiety with their child's math anxiety, and the downstream effects of math anxiety on math education outcomes. The first study addressed a gap in the literature by examining parents' own math anxieties (Gunderson et al., 2012; see Maloney et al., 2015). Results confirmed expectations that parents' anxiety is related to children's anxiety and these two variables interact to predict math education outcomes. In doing so, the first study also advances our knowledge of the gendered nature of the intergenerational transfer of math anxiety (Gniewosz and Noack, 2012). The results for mother-daughter dyads were mixed, supporting the hypothesis when daughters' and mothers' math anxiety were both low, but not consistently supporting hypotheses when daughters' and mothers' math anxiety were both high. Future research should further examine the mixed results by measuring possible moderating variables such as the extent to which mothers are involved in daughters' math education, such as helping with homework (see Maloney et al., 2015). It may be the case that for daughters whose mother does not help much, daughters' own math anxiety is a better predictor of math self-efficacy, behavioral intentions, and math devaluing. However, when mothers are actively involved in helping daughters with math homework, the predicted interaction of low-low and high-high parent-child math anxiety may reflect the hypothesized relationships.

Results from study 1 indicate that parents' anxiety plays a role in children's math anxiety and the variables interact to predict several math education outcomes including math self-efficacy, math GPA, math behavioral intentions, math attitudes, and math devaluing. Consistent with existing literature, children with greater math anxiety had lower math self-efficacy, lower math GPA, lower math behavioral intentions, more negative math attitudes, and greater math discounting. However, more interesting was the interaction of children's math anxiety with parents' math anxiety within gendered dyads. The same-gender parent-child dyads showed the most significant relationships, and more specifically the Mother-Daughter dyad dominated the findings. The Mother-Daughter dyads' math anxiety predicted math self-efficacy, math behavioral intentions, math attitudes, and math devaluing. The general pattern was consistent with the hypothesis that when both mothers' and daughters' math anxiety were low, daughters had more positive math outcomes compared to when mothers' and daughters' math anxiety were both high, with exceptions as discussed previously.

Interestingly, the Father-Son dyad was the only one to show a significant relationship to GPA. When both fathers and sons had lower math anxiety, math GPA was higher. Fortunately, even when fathers' math anxiety was higher, if sons had lower math anxiety, GPA was higher. Only when both fathers and sons had higher math anxiety was GPA lower. This finding is novel and should be replicated in future studies. Mothers' anxiety did not predict daughters' GPA, thus there may be other variables intervening in this relationship that are not present in the Father-Son dyad. This likely reflects the gendered nature of math stereotypes and the fact that girls and women are more negatively impacted by cultural biases.

Study 2 addressed a call for a mechanistic approach (Gunderson et al., 2012), and demonstrated that math anxiety is a mechanism through which math-gender stereotypes negatively influence performance related math outcomes for *both* girls and boys. Further, the results suggest that endorsement of math-gender stereotypes may be an antecedent for developing math anxiety for both boys and girls.

In sum, two studies contributed to the existing literature by helping to address several gaps. First, there is only one known published study that found effects of parents' math anxiety on children's math education outcomes, particularly their math performance (Maloney et al., 2015). Second, this study examined these relationships using a gendered lens and found support for the gender stereotype literature that the transmission of math anxiety seems most prevalent among same-gender parent-child dyads, particularly the Mother-Daughter dyad. Further, the results provided initial evidence that the socialization of, and endorsement of math-gender stereotypes among girls and boys is related to negative math achievement.

Limitations

Although the studies make novel contributions to the literature, they are not without weaknesses. First, the data are correlational and cross-sectional. Longitudinal data over at least a full school year would be more informative regarding potential causal relationships. Although the mediational analyses for performance outcomes held after testing for reverse mediation, a stronger case for causality and direction of effects can be made with longitudinal data.

A drawback of Study 1 is that only one parent completed the questionnaire, limiting the full test of the gender of parent who might be most influential on daughters and sons. It can be argued that the parent completing the questionnaire may be the one most involved in the child's math education, but this assumption is tenuous. Further, the sample size of fathers was smaller, which perhaps made the analysis of Father-Daughter and Father-Son dyads underpowered. The fathers who did participated may be particularly good in math and therefore the results with fathers may not be representative of the full spectrum of Father-Daughter and Father-Son relationships regarding math education.

The response rate in Study 1 was 51%, thus the sample of parents who participated is likely different in some ways than parents who did not participate. Without data on non-participating parents, this is difficult to know. We do know that the children whose parents participated did vary in some systematic ways from children whose parents did not participate[2]. Further, the sample of parents reflects racial,

[2]In the United States, grades in school reflect the level of one's education. Sixth grade is either the final year of elementary school education, or the first year of middle school education. Seventh and eighth grades are typically offered in middle schools, which is the educational period before high school where students earn their diploma. Honors math classes indicate the students are high achieving and are over-qualified for the math classes offered to most students. In the United States, students are often tracked into higher level math classes, such as ones to prepare

ethnic, and national diversity. There may be cultural differences in norms regarding parental involvement in children's math education that are not captured in this study[3].

Implications

Despite these limitations the studies provide several contributions to the literature and the data can be used to inform school-based interventions. For example, stereotype busting interventions for teachers, parents, and students may be helpful. Given that several meta analyses show there is no longer a gender gap in math performance (Hyde et al., 2008; Lindberg et al., 2010), educators need to spread awareness to break down gender stereotypes as a barrier to math achievement. Further, anti-math anxiety training seems to be critical for math teachers and parents, particularly mothers. Such training can help boost math self-efficacy, which can be transmitted to students (Hendel and Davis, 1978; Tooke and Lindstrom, 1998; Gresham, 2007). Similarly, parents need to know about the subtle effects they may have on their children in communicating their own math anxiety. It is well known that parental involvement in students' education influences academic outcomes (Jeynes, 2007). Educational campaigns to promote parental involvement and educate parents on the importance of math education for all students might help encourage parents to support their children's math education endeavors. Specifically, educating parents on the impact that their beliefs and actions may have on their children's academic success would be of benefit.

Finally, schools should implement math anxiety reducing workshops for students. All students, girls and boys, will benefit from lower math anxiety. Perhaps what is ultimately needed is an overhaul of the US education system to focus less on competition and testing and more on collaboration and learning. Research has shown that when there is less focus on getting the right answers, and providing students with social support, students show less math anxiety (Turner et al., 2002). Also, when teachers emphasize incremental intelligence, working hard and making mistakes to learn, students have better academic achievement (Dweck, 2006).

them for college, and these courses are often called "honors" courses or advanced placement.

[3]We thank an anonymous reviewer for pointing this out.

AUTHOR NOTE

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01597

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 15 October 2015
doi: 10.3389/fpsyg.2015.01596

Insecure attachment is associated with math anxiety in middle childhood

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Children's anxiety for situations requiring mathematical problem solving, a concept referred to as math anxiety, has a unique and detrimental impact on concurrent and long-term mathematics achievement and life success. Little is known about the factors that contribute to the emergence of math anxiety. The current study builds on the hypothesis that math anxiety might reflect a maladaptive affect regulation mechanism that is characteristic for insecure attachment relationships. To test this hypothesis, 87 children primary school children (M_{age} = 10.34 years; SD_{age} = 0.63) filled out questionnaires measuring insecure attachment and math anxiety. They all completed a timed and untimed standardized test of mathematics achievement. Our data revealed that individual differences in math anxiety were significantly related to insecure attachment, independent of age, sex, and IQ. Both tests of mathematics achievement were associated with insecure attachment and this effect was mediated by math anxiety. This study is the first to indicate that math anxiety might develop in the context of insecure parent–child attachment relationships.

Keywords: mathematics achievement, insecure attachment, math anxiety, mediation

OPEN ACCESS

Edited by:
Erin Anne Maloney, The University of Chicago, USA

Reviewed by:
Alex M. Moore, University of Missouri, USA
Alana Eve Dulaney, The University of Chicago, USA

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *17 June 2015*
Accepted: *02 October 2015*
Published: *15 October 2015*

Citation:
Bosmans G and De Smedt B (2015) Insecure attachment is associated with math anxiety in middle childhood. Front. Psychol. 6:1596. doi: 10.3389/fpsyg.2015.01596

INTRODUCTION

Thereis growing consensus that individual differences in mathematics achievement are not merely a product of cognitive factors, such as numerical magnitude processing (e.g., De Smedt et al., 2013) or working memory (e.g., Friso-Van den Bos et al., 2013),but that such differences are also partially explained by the anxiety to perform tasks involving mathematical problem solving, a concept that has been referred to as math anxiety (e.g., Ma, 1999; Ashcraft et al., 2007; Maloney and Beilock, 2012; Young et al., 2012). Accumulating evidence suggests that from middle childhood onward, some individuals are more prone to develop this math anxiety, which has been defined as "feelings of tension and anxiety that interfere with the manipulation of numbers and the solving of mathematical problems in a wide variety of ordinary life and academic situations" (Richardson and Suinn, 1972, p. 551). Because math anxiety not only impacts on mathematical skills, but also has adverse effects on career choice, employment, and professional success (e.g., Ma, 1999), especially in view of our numerate western society, research is needed to better understand the characteristics of individuals with elevated levels of math anxiety in order to develop appropriate interventions. Against the background of research on broader anxiety-related problems, which has convincingly shown that such problems result from maladaptive coping strategies that some children develop in the context of insecure attachment relationships (Brumariu and Kerns, 2010; Vasey et al., 2014), the present study investigated for the first time the hypothesis that individual differences in math anxiety reflect differences in attachment security.

Various studies have shown that math anxiety has a negative impact on mathematics achievement (e.g., Ashcraft et al., 2007). More specifically, math anxiety disrupts general cognitive capacities, such as working memory resources (e.g., Ashcraft and Kirk, 2001), as well as specific numerical processing skills, such as symbolic magnitude processing (Maloney et al., 2011) and counting (Maloney et al., 2010), that are needed for successful mathematics performance. On the other hand, it leads to the avoidance of mathematics (e.g., Lyons and Beilock, 2012a,b; Maloney and Beilock, 2012). This is nicely illustrated by recent neuroimaging data which indicate that in high math anxious individuals, even the anticipation of performing a mathematical task elicits an increased neural response in brain regions related to visceral threat detection and the experience of pain, including bilateral posterior insula (Lyons and Beilock, 2012a), as well as regions related to cognitive control and the processing of negative emotions, such as the bilateral inferior frontal junction (Lyons and Beilock, 2012b).

While most of the existing body of evidence has focused on adolescents and college students, pointing to a moderate association (r between −0.27 and −0.31) between math anxiety and mathematical performance (for meta-analyses see Hembree, 1990, $r = -0.27$; Ma, 1999, $r = -0.31$), there is an emergent, yet limited, number of studies that is examining the effect of math anxiety on mathematical performance in primary school children. These data converge to the conclusion that already at this young age elevated levels of math anxiety are associated with poorer mathematics achievement (e.g., Devine et al., 2012; Wu et al., 2012; Young et al., 2012) and that increased levels of mathematical anxiety in second grade coincided with lower gains in children's mathematics achievement from second to third grade (Vukovic et al., 2013). This association between math anxiety and mathematics achievement is not explained by trait anxiety (Wu et al., 2012) or by test anxiety (Devine et al., 2012). Recent neuroimaging data are beginning to shed light on the neural underpinnings of math anxiety in children (Young et al., 2012). These authors showed that in 7–9-years-old heightened levels of math anxiety are related to increased activity in regions of the right amygdala that are associated with the processing of negative emotions and to decreased activity in posterior parietal and dorsolateral prefrontal cortex networks that are typically recruited during mathematical reasoning.

Although studies that aim to understand individual differences in math anxiety in young children are emerging slowly, research on the origin of broader anxiety-related problems has a much more established tradition (Bernstein et al., 1996). These data have convincingly shown that anxiety-related problems result from the maladaptive coping strategies that some children develop in the context of insecure attachment relationships (Brumariu and Kerns, 2010; Vasey et al., 2014). Bowlby (1969) proposed that the attachment system and the anxiety system are intrinsically interwoven. To promote survival, threat activates the attachment system directing children's motivational focus toward proximity and support seeking (Cassidy, 2008). Depending on whether or not parents are subsequently experienced as providing responsive support, children will develop either secure or insecure attachment expectations regarding mother's future availability as a source for support (Bowlby, 1969). Research suggests that insecure attachment fundamentally alters children's ability to cope with distress, explaining links between attachment and anxiety-related problems (Brumariu et al., 2012). While securely attached distressed children easily seek parental support, insecurely attached distressed children cannot confidently rely on their parents. Hence, they rely on less adaptive, secondary attachment-related coping strategies (Mikulincer and Shaver, 2007; Brenning et al., 2011a). These latter strategies depend on children's predominant insecure attachment style. More anxiously attached children continue seeking parental support, but their fear that parents will not support them hyper-activates negative emotions, which makes them hyper-vigilant for sources of distress. More avoidantly attached children distance themselves from parents. They no longer seek support, but they deactivate or suppress all emotions and behaviorally avoid sources of distress. In line with the assumption that both maladaptive emotion regulation strategies put children at risk to develop anxiety problems (Vasey et al., 2014), attachment anxiety and attachment avoidance have both been linked with the emergence of anxiety problems (Bar-Haim et al., 2007; Groh et al., 2012).

The hypothesis that math anxiety might be determined by insecure attachment could provide an important link to explain intriguing previous research findings, which demonstrate that insecure attachment predicts poor mathematics achievement (e.g., Keller et al., 2008). To date, attachment theory has failed to provide a strong explanation of this effect, but math anxiety might represent one of the underlying mechanisms. More specifically, it seems reasonable to assume that more anxiously attached children make more mistakes during tasks that involve mathematical problem solving, because their elevated levels of math anxiety during these tasks consume their working memory resources they need to successfully complete these tasks (Mattarella-Micke et al., 2011). Additionally, it is reasonable to assume that more avoidantly attached children might avoid seeking help of parents' and/or teachers' while studying, which, in turn, might lead to less proficiency in academic domain knowledge and increased anxiety when they have to perform in that academic domain. This leads to the prediction that the link between insecure attachment and poor mathematics achievement might be mediated by math anxiety.

The Present Study

The present study is the first to test the hypothesis that individual differences in math anxiety are explained by insecure attachment. We verified whether increased levels of math anxiety were associated with insecure attachment. In addition, we investigated whether math anxiety mediated the previously observed association between insecure attachment and poor mathematics achievement.

The abovementioned hypotheses were tested in a randomly selected sample of fifth graders. We focused on fifth grade because middle childhood is the age period during which math anxiety emerges (e.g., Ma, 1999) and research at this age might have more power to identify associated risk factors. On the other hand, an increasing number of attachment-related studies emphasize that studying attachment in this age-group is essential to understand long-term development of anxiety problems (Bosmans et al., 2014).

Although both parents are equally important attachment figures to understand links between attachment and mathematics achievement (Keller et al., 2008), the current study only focused on attachment to the mother, in order to limit the number of questionnaires that had to be completed by the (young) participants. Mathematics achievement was investigated by means of timed as well as untimed standardized mathematics tests. To evaluate whether the associations between insecure attachment, math anxiety and mathematics achievement were not explained by general intellectual abilities, a measure of intelligence was administered.

MATERIALS AND METHODS

Participants

Participants were 87 children (46 girls) that were randomly selected from three Flemish primary schools. They all were attending fifth grade and their mean age was 10.34 years ($SD = 0.63$). The children came from a variety of socioeconomic backgrounds. The parents of 15 children were divorced and 4 children had a deceased father. Eighty-five children filled out the attachment questionnaires about their biological mother, two children reported on their relationship with their stepmother.

Procedure

Parents were informed about the study via letters distributed in the classroom, and they all gave consent for participation. Children were tested at their own schools during school hours. All measures were group administered.

Measures

Attachment

Children completed an adapted version of the Experiences in Close Relationships Scale-Revised (ECR-R; Fraley et al., 2000, adapted for children as the ECR-RC by Brenning et al., 2011b). The ECR-RC assessed the two dimensions central in attachment-related affect regulation: attachment anxiety and avoidance in relationship to the mother. Attachment anxiety was measured with 18 items tapping into feelings of fear of abandonment and strong desires for interpersonal merger (e.g., "I worry about being abandoned by my mother"). Attachment avoidance was assessed with 18 items tapping into discomfort with closeness, dependence, and intimate self-disclosure (e.g., "I prefer not to show to my mother how I feel deep down"). Items were rated on a seven-point Likert scale ranging from not at all (= 1) to very much (= 7). Both subscales have strong internal consistency and validity (Brenning et al., 2011b). Cronbach's αs of the ECR-RC in this study were 0.90 and 0.80 for attachment anxiety and avoidance, respectively.

Math Anxiety

The Mathematics Anxiety Rating Scale for Adolescents (MARS-A; Suinn and Edwards, 1982) was adapted to use with primary school children. The original questionnaire was reduced to 15 items that described mathematical situations with which children are often confronted with (e.g., "How nervous are you when you are called during math class"). Children were asked to indicate on a five-point Likert scale how anxious they were in these situations, ranging from not at all (= 1) to very anxious (= 5). This test had a high internal consistency in the current sample, i.e., Cronbach $\alpha = 0.88$.

Mathematics Achievement

Two standardized mathematics achievement tests were administered. The Tempo Test Arithmetic (de Vos, 1992) was used as a timed measure of mathematics achievement. In this test, children had to solve basic arithmetic combinations (e.g., 6 + 5) of increasing difficulty as fast and accurately as possible. The test consisted of five columns of 40 items, comprising additions, subtractions, multiplications, divisions, and mixed problems. For each column, children had to solve as many problems as possible within 1 min. The total number of correctly solved problems across all columns was used in all subsequent analyses. We also administered the untimed curriculum-based standardized achievement test of mathematics (Dudal, 2000). This test consisted of 60 items that covered a wide range of mathematical skills, such as number knowledge, calculation, word problem solving, measurement, and geometry. The total number of correctly solved items was used in all subsequent analyses.

Intelligence

Raven's Progressive Matrices (Raven et al., 1992) was used as a measure of children's intellectual ability. The test consists of 60 items and raw scores were used in all analyses.

RESULTS

Preliminary Analyses

Descriptive statistics of the variables under study are reported in **Table 1**. All variables were well-distributed with no floor or ceiling effects. There were no sex differences (*p*s: 0.13–0.97), except for the timed mathematics achievement test [$F(1,85) = 4.48$, $p = 0.037$] on which girls had lower scores ($M = 71.02$, $SD = 11.60$) than boys ($M = 76.12$, $SD = 10.76$).

Math Anxiety and Insecure Attachment

Both measures of insecure attachment were significantly related to mathematics anxiety (**Table 1**), indicating that children with less secure attachment showed higher levels of mathematics anxiety. We next calculated partial correlations with age, sex, and IQ as control variables to verify whether these associations were

TABLE 1 | Correlation and descriptive statistics ($n = 87$).

	1	2	3	4	5	6
(1) Math anxiety	–					
(2) Attachment anxiety	0.25*	–				
(3) Attachment avoidance	0.27*	0.54***	–			
(4) Timed math	−0.42***	−0.18†	−0.01	–		
(5) Untimed math	−0.43***	−0.31*	−0.16	0.46***	–	
(6) IQ	−0.43***	−0.14	−0.09	0.26*	0.58***	–
M	25.30	2.28	2.54	73.43	41.43	42.47
SD	7.80	0.98	0.87	11.44	10.07	5.98
Minimum	15	1.00	1.00	46	14	24
Maximum	48	5.00	4.72	92	57	55
Maximum possible	75	7.00	7.00	120	60	60

†$p < 0.1$; *$p < 0.05$; ***$p < 0.001$.

TABLE 2 | Confidence intervals around unstandardized regression coefficients for indirect effects.

	Timed math 95% CI indirect effect		Untimed math 95% CI indirect effect	
Attachment anxiety	−2.15 <	< −0.11	−1.79 <	< −0.02
Attachment avoidance	−2.92 <	< −0.31	−2.24 <	< −0.18

affected by age, sex, or intelligence. When controlling for age, the associations between insecure attachment and mathematics anxiety remained significant (attachment anxiety: $r_p = 0.21$, $p = 0.048$; attachment avoidance $r_p = 0.24$, $p = 0.023$). Similarly, these associations remained significant when sex (attachment anxiety: $r_p = 0.24$, $p = 0.029$; attachment avoidance: $r_p = 0.27$, $p = 0.012$) and IQ (attachment anxiety: $r_p = 0.22$, $p = 0.048$; attachment avoidance: $r_p = 0.25$, $p = 0.019$) were taken into account.

Insecure Attachment, Math Anxiety, and Mathematics Achievement

The correlations in **Table 1** showed the expected negative association between math anxiety and timed as well as untimed measures of mathematics achievement. On the other hand, attachment anxiety correlated with mathematics achievement, in particular with the untimed test. In the next mediation analyses, we explored whether math anxiety mediated the association between insecure attachment and poor mathematics achievement.

We tested this mediation hypothesis by following recommendations by MacKinnon et al. (2004), with a non-parametric resampling bias-corrected bootstrap approach with 10.000 resamples drawn with replacement from the original sample ($n = 87$) to derive the confidence interval (CI) for the unstandardized regression coefficient of the indirect effect (Hayes, 2009). The indirect effect through math anxiety was considered as significant when 0 was not part of the CI. To test the significance of the indirect effect, we performed four mediation analyses using Model 4 of the PROCESS Macro provided by Hayes (2013) with attachment as predictor, math anxiety as mediator, and the two mathematics achievement measures as criterion variables. If the indirect effect is significant, mediation has occurred. To control for effects of age and sex, all mediation analyses were carried out with these variables as control variables.

When predicting *timed mathematical achievement*, the initial marginally significant association with attachment anxiety was reduced to non-significance after taking into account the effect of Math Anxiety ($\beta = -0.07$, $p = 0.54$). Zero was not part of the 95% CI around the indirect effect (**Table 2**), suggesting that math anxiety mediated the link between attachment anxiety and timed mathematical achievement. The entire model explained 20% ($p < 0.001$) of the variance in timed mathematical achievement. Even though there was no direct effect of attachment avoidance on timed mathematical achievement, there is accumulating evidence, which suggests that absent direct effects could be the result of significant indirect effects; this leads to the recommendation to test for indirect effects in spite of absent direct effects (Rucker et al., 2011). Confirming the accumulating evidence, and in line with our expectations, the indirect effect of math anxiety on the association between attachment avoidance and timed mathematical achievement was significant (**Table 2**). The entire model explained 21% ($p < 0.001$) of the variance.

When predicting *untimed mathematical achievement*, the initial significant association with attachment anxiety, was reduced, but remained significant after taking into account the effect of math anxiety ($\beta = -0.22$, $p = 0.03$). The indirect effect was significant (**Table 2**) suggesting that math anxiety mediates the link between attachment anxiety and untimed mathematical achievement. The entire model explained 23% ($p < 0.001$) of the variance in untimed mathematical achievement. Although the initial direct effect of attachment avoidance on untimed mathematical achievement was not significant ($\beta = -0.05$, $p = 0.65$) after taking into account math anxiety, the indirect effect was significant (**Table 2**) and the entire model explained 19% ($p < 0.001$) of the variance in untimed mathematical achievement.

As a final step, we evaluated whether the mediation effects remained when children's intelligence was taken into account as a control variable. The mediation effects were largely unaffected by intelligence, except for the indirect effect of Attachment Anxiety on Untimed Mathematical Achievement, which was slightly suppressed, but remained marginally significant (90% CI: $-1.15 < b < -0.05$).

DISCUSSION

There is an increasingly emerging literature that stresses the importance of affect regulation mechanisms in individual differences in academic competence. In the context of mathematics achievement, research has pointed to the detrimental role of mathematics anxiety on mathematical performance (e.g., Hembree, 1990; Ma, 1999; Ashcraft et al., 2007). The current study is the first to investigate whether children's emerging mathematical anxiety could be related to insecure attachment, and whether mathematical anxiety explains the associations between insecure attachment and mathematics achievement. Our data suggest that higher levels of mathematics anxiety are associated with insecure attachment and that mathematical anxiety mediates the association between insecure attachment and mathematical achievement. In other words, these data indicate that less securely attached children are more likely to show math anxiety, and therefore are more vulnerable to perform poorly on mathematical tasks. As such, these data highlight the importance of considering children's insecure attachment when studying the origins of math anxiety.

In line with the existing body of evidence, the current study observed and replicated the significant association between mathematics anxiety and mathematical achievement in primary school children (Devine et al., 2012; Wu et al., 2012; Young et al., 2012; Vukovic et al., 2013). It is interesting to note that this association was observed for timed as well as untimed standardized tests of mathematical performance, which suggests that mathematics anxiety is linked to both time-pressured and non-pressured testing situations.

Individual differences in mathematical anxiety were significantly related to insecure attachment. These associations were independent of age, sex, and IQ. The current data are the first to indicate that insecure attachment toward the mother might be an important contextual factor related to children's math anxiety. This finding suggests that adverse social factors could contribute to individual differences in children's mathematical anxiety. Unfortunately, the current study's cross-sectional research design does not allow us to draw conclusions about the time course of these associations. It remains to be seen whether insecurely attached children are at risk to develop math anxiety, or vice versa, or that the association between these two non-cognitive factors is bidirectional. This all motivates longitudinal research in which attachment is investigated as a possible predictor of subsequent math anxiety development.

Math anxiety mediated the association between attachment and mathematical performance. This indicates that math anxiety might be an underlying mechanism for the previously observed associations between insecure attachment and poor mathematics achievement (e.g., Keller et al., 2008). It might be contended that less securely attached children make more errors during mathematical problem solving due to their elevated levels of math anxiety. It also might be that children who choose to not seek help from parents or teachers, due to insecure attachment, would be less likely to receive help in mathematics from parents or teachers, thus leading to less proficient domain knowledge. Future studies should explore these possibilities more directly.

The observed pattern of associations appeared to be specific and was not explained by recourse to intelligence. Also, findings were similar for both timed and untimed measures of mathematics achievement, which indicates that insecurely attached children's levels of math anxiety increases for mathematics in general and not only when they have to perform under time pressure. The interrelations between insecure attachment and math anxiety accounted for 18–23% of the variance in children's mathematical performance and point to an important role of these non-cognitive factors in explaining individual differences in mathematics achievement, yet future studies should explore how these non-cognitive factors interact with other well-known cognitive predictors of mathematics achievement, such as numerical magnitude processing (e.g., De Smedt et al., 2013) or working memory (e.g., Friso-Van den Bos et al., 2013).

The current findings provide the first indication that attachment-related factors are important to understand math anxiety, yet some limitations need to be taken into account when evaluating the conclusions of the present study. One limitation deals with our use of self-reported attachment and math anxiety measures and this might have affected our findings. Attachment researchers have traditionally raised concerns regarding the validity of self-reported attachment (Ainsworth, 1985). More specifically, self-report is considered vulnerable for underreporting insecure attachment, and narrative measures, such as attachment interviews are generally considered to be more appropriate because they are less vulnerable to defensive response styles (e.g., Main et al., 1985). However, psychometric research on middle childhood attachment increasingly shows that these concerns are not applicable to this age-group, as these children appear to respond similarly to self-report and narrative measures (e.g., Psouni and Apetroaia, 2014) and both measurement approaches are equally valid indicators of adverse developmental outcomes (Kerns et al., 2007). Relatedly, self-reported anxiety problems are also vulnerable to defensive underreport, yet validation research has demonstrated that self-report is the most valid strategy to identify anxiety-related problems (e.g., Achenbach et al., 1987). One important avenue for future research might be to combine self-reports with real-time physiological measures of stress and anxiety. Such approach has been successfully applied in studying the association between anxiety and attachment (e.g., Gilissen et al., 2008), and it therefore might be particularly useful to collect such physiological data immediately before or during the execution of mathematical problem solving tasks.

The current study only focused on attachment toward mother. The question remains whether the similar effects are observed for other attachment figures like fathers or grandparents. Future research should therefore include the role of attachment to fathers too, because research suggests that a good relationship with father can buffer the negative effect of mother on children's anxiety development (e.g., Bögels and Phares, 2008).

An important limitation of the current study was that it did not include measures of trait anxiety and general anxiety. It indeed cannot be excluded that the association between attachment and math anxiety only reflects that trait anxious children are both more likely to be insecurely attached and to display math anxiety problems. Against the background of previous research, such an explanation seems less likely. Specifically, attachment research has convincingly shown that differences in attachment security are not linked to temperament (Vaughn et al., 2008). Similarly, research suggests that math anxiety and trait anxiety are different constructs (Devine et al., 2012; Wu et al., 2012). While this suggests that controlling for trait anxiety would not have changed the results of the current study, it remains important to rule out this alternative explanation. On the other hand, it would be interesting to investigate to what extent the observed association between insecure attachment and math anxiety merely reflects a general anxiety effect. It is possible that for insecurely attached children math anxiety is part of a broader anxiety problem. For example, if an insecurely attached child has difficulties with math or is exposed to a high degree of negative attitudes about math, it might develop math anxiety. This math anxiety could lead to lower math achievement through either transient reductions in working memory or the avoidance of mathematics. These possibilities should be explored in future studies. Our findings have important implications for the development of new intervention strategies. Current practices to address math anxiety include not only techniques that are used to overcome other types of anxiety, such as desensitization (e.g., Brunyé et al., 2013), but also more specific methods that aim to address the origins of math anxiety, such as the improvement of math learning experiences (e.g., Kramarski et al., 2010). In view of the current data that children with insecure attachment are vulnerable to the development of math anxiety, and consequently to poor math performance, interventions that are tailored to insecure attachment-related mechanisms might be particularly useful. For example, research on teacher–child relationships in insecurely attached children has shown that teacher sensitivity can buffer against the maladaptive effects of children's insecure attachment (Buyse et al., 2011). It is therefore likely that improving teachers' skills to respond sensitively to children might decrease insecurely attached children's math anxiety and increase their mathematics achievement.

ACKNOWLEDGMENTS

The authors are grateful to all schools and children who participated in this research. The authors would like to thank Loes De Cooman and Lindsay Willems for their assistance with data collection. This work is supported by grants G.0934.12 and G.0774.15 of the Research Foundation Flanders (FWO), and grants OT/12/043 and CREA/12/004 from the Research Fund KU Leuven, Belgium, awarded to Guy Bosmans, and grant GOA 2012/010 of the Research Fund KU Leuven, Belgium, awarded to Bert De Smedt.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 17 September 2015
doi: 10.3389/fpsyg.2015.01404

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Gender stereotype endorsement differentially predicts girls' and boys' trait-state discrepancy in math anxiety

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *25 June 2015*
Accepted: *02 September 2015*
Published: *17 September 2015*

Citation:
Bieg M, Goetz T, Wolter I and Hall NC (2015) Gender stereotype endorsement differentially predicts girls' and boys' trait-state discrepancy in math anxiety. Front. Psychol. 6:1404. doi: 10.3389/fpsyg.2015.01404

Mathematics is associated with anxiety for many students; an emotion linked to lower well-being and poorer learning outcomes. While findings typically show females to report higher trait math anxiety than males, no gender differences have to date been found in state (i.e., momentary) math anxiety. The present diary study aimed to replicate previous findings in investigating whether levels of academic self-concept was related to this discrepancy in trait vs. state anxiety measures. Additionally, mathematics-related gender stereotype endorsement (mathematics is a male domain) was investigated as an additional predictor of the trait-state discrepancy. The sample included 755 German 9th and 10th graders who completed self-report measures of trait math anxiety, math self-concept, and gender stereotype endorsement, in addition to state measures of anxiety after math classes by use of a standardized diary for 2–3 weeks ($N_{\text{within}} = 6207$). As expected, females reported higher trait math anxiety but no gender differences were found for state math anxiety. Also in line with our assumptions, multilevel analyses showed the discrepancy between trait and state anxiety to be negatively related to students' self-concept (i.e., a lower discrepancy for students with higher self-concepts). Furthermore, gender stereotype endorsement differentially predicted the trait-state discrepancy: When controlling for self-concept in mathematics, females who endorsed the gender stereotype of math being a male domain more strongly overestimated their trait math anxiety as compared to their state anxiety whereas this effect was not significant for males. The present findings suggest that gender stereotype endorsement plays an important role in explaining gender differences in math anxiety above and beyond academic self-concept. Implications for future research and educational practice are discussed.

Keywords: anxiety, mathematics, self-concept, gender stereotype, trait anxiety, state anxiety, ecological momentary assessment, diary study

Introduction

Mathematics is a domain of high importance, given the need for basic mathematical competencies in many degree programs and professional careers, making the frequent reports of math anxiety by students a cause for concern (Goetz et al., 2004, 2014). In general, greater anxiety has been found to contribute to lower well-being (Diener, 2000) and poorer achievement outcomes, as well as lower long-term academic motivation and use of more superficial learning strategies (Pekrun et al., 2002). Research further shows higher levels of math anxiety to negatively predict decisions in favor of course enrollment and career choices in math-intensive fields (Eccles, 1985; Wigfield et al., 2002; Perez et al., 2014).

Meta-analyses consistently show female students to report higher levels of mathematics anxiety (e.g., Else-Quest et al., 2010), with studies additionally showing female students typically report lower self-concepts in mathematics relative to male students (Hyde et al., 1990; Goetz et al., 2008, 2013). These gender differences are, however, in direct contrast to studies showing gender differences in mathematics performance to be notably small or non-existent (Hyde et al., 2008; Else-Quest et al., 2010), and instead appear to reflect long-held stereotypes that female students are less capable in this domain relative to their male counterparts (Steffens et al., 2010; Steffens and Jelenec, 2011). This troubling persistence of gender stereotypes and females' negative attitudes toward mathematics is further assumed to contribute to the underrepresentation of females in many STEM domains in which mathematical competencies are a prerequisite (Watt, 2006; Halpern et al., 2007).

With respect specifically to math anxiety, previous research has been almost exclusively based on self-reports of trait-like anxiety as opposed to state assessments utilizing real-time measures. We define trait and state math anxiety from a methodological perspective (see Bieg et al., 2013). Reports of trait math anxiety reflect (mentally) generalized levels of anxiety across different time points in math-related situations. In contrast, reports of state math anxiety reflect levels of momentary anxiety in real-life math-related situations. Thus, the primary difference between trait and state math anxiety, as we define it, is the different level of generalization across time (see Pekrun, 2006). The ecological validity of such trait-based measures regarding their potential to capture emotions as they are experienced has been questioned due to their reliance on retrospective or global reports and resulting susceptibility to recall bias (Scollon et al., 2003). Although both trait and state measures are assumed to assess anxiety, these assessment methods can lead to very different results with respect to the degree to which specific emotions are reported (Bieg et al., 2014). Thus, an intriguing question remains as to the extent to which the gender differences observed on self-report trait measures of habitual math anxiety reflect actual gender differences in the lived experience of anxiety in the mathematics domain.

One recent study found gender differences in students' trait but not state mathematics anxiety, with girls reporting higher levels than boys on trait measures, but not on the state measures (Goetz et al., 2013). Emotion levels are also typically found to be higher on trait assessments as compared to state measures (intensity bias; Buehler and McFarland, 2001; Levine et al., 2006). Further, such discrepancies between trait self-reports and state anxiety measures—differences that could be interpreted as a measure for the discrepancy between perceived as compared to actual anxiety—has been found to be largely explained by students' perceptions of competence (e.g., academic self-concept; Goetz et al., 2013; Bieg et al., 2014) underscoring the potential for trait assessments to be more strongly biased by subjective beliefs (Robinson and Clore, 2002). Accordingly, individuals' beliefs regarding gender stereotypes can also be assumed to influence trait reports more than state reports of emotions, with the endorsement of math-related gender stereotypes likely playing a role, particularly for females, in the trait-state discrepancy. The role of math-related gender stereotypes as moderators of the trait-state discrepancy in students' math anxiety, however, to date remains unexplored.

Theoretical Background

Math as Gender-stereotyped Domain

Mathematics has long been viewed as a typically male domain; an assumption that continues to be observed in research on gender stereotypes in educational settings (Plante et al., 2009; Steffens et al., 2010; Cvencek et al., 2011; Steffens and Jelenec, 2011; Passolunghi et al., 2014). Stereotypes are defined as the attributions people make regarding the abilities and characteristics of members of a certain group and assumptions about how members of the stereotyped group typically behave (Ruble et al., 1984; Eagly et al., 2000). Although stereotypes are assumed to facilitate human behavior and decision-making in complex environments, they nonetheless are consistently found to have negative effects for the stereotyped group (e.g., stereotype threat effect; Steele and Aronson, 1995; Schmader et al., 2004; Maloney et al., 2013). With respect to the domain of mathematics, research shows males to hold stronger gender stereotypes than females (e.g., Hyde et al., 1990; Rowley et al., 2007) with the endorsement of math-related gender stereotypes found to predict more negative attitudes regarding math ability, and possibly lower involvement in mathematics-related professions, for female students (Eccles, 1994; Schmader et al., 2004; Kurtz-Costes et al., 2008). Research shows multiple sources can contribute to the formation of gender stereotypes in mathematics such as the math anxiety and beliefs of female teachers and parents (Beilock et al., 2010; Gunderson et al., 2012).

Gender Differences in Math-related Attitudes and Anxiety

Meta-analyses of international research typically show small or no gender differences in math performance (Else-Quest et al., 2010; Lindberg et al., 2010; Hyde, 2014; Voyer and Voyer, 2014). Research on math-related attitudes, however, has found individuals' attitudes regarding mathematics to vary to a much higher degree, with girls tending to report less positive attitudes (Watt, 2004; Nagy et al., 2008) and higher levels of anxiety regarding mathematics than boys (Hyde et al., 1990; Else-Quest et al., 2010). It is important to note that most of this research has investigated mathematics anxiety using trait assessments that, as noted above, may not as accurately reflect *in-situ* emotional experiences as would state assessments.

Assessment of Students' Math Anxiety and the Accessibility Model of Emotional Self-report

There are various possible methods for assessing students' math anxiety. Most typically, students are asked about their math anxiety "in general" as a measure of habitual or trait anxiety, with more ecologically valid momentary or state assessments tending to be underutilized (Scollon et al., 2009; Schwarz, 2012). In their accessibility model of emotional self-report, Robinson and Clore (2002) attempt to account for this discrepancy in ecological validity in suggesting that trait assessments of emotional self-reports are more strongly influenced by semantic memory (subjective beliefs, stereotypic beliefs). According to the theory, it can be assumed that because of the transient nature of emotions, it is not possible to directly retrieve emotions from memory. However, when one is asked about emotions "in general," there is a process of evaluation and aggregation that occurs. It is at this point where recall biases and subjective beliefs may come into play. In contrast, state assessments are more direct in nature and therefore assumed to be less prone to influences by personal beliefs and recall biases, with several studies having provided empirical evidence in support of this assumption (Barrett, 1997; Robinson and Clore, 2002).

Moderators of the Trait-state Discrepancy

Recent research shows mean levels of emotion reports to differ substantially between trait and state measures, with trait emotion levels in mathematics (including anxiety) being usually higher than those for state emotions (Bieg et al., 2014). A recent study by Goetz et al. (2013) with 5th to 10th graders found gender differences in trait math anxiety (lower levels for boys) but not in state math anxiety. Furthermore, the discrepancy between trait and state assessments, which could be interpreted as the comparison of retrospective perceptions to actual experiences of anxiety, was largely accounted for by students' self-concept in mathematics such that students' with higher self-concepts were found to have a lower trait-state discrepancy in math anxiety.

In addition to identity-related beliefs such as self-concept, gender stereotypes are explicitly addressed in Robinson and Clore's (2002) accessibility model as an element of semantic memory that can bias trait self-report measures. Accordingly, the gender stereotype in mathematics can be assumed to play a role in the trait-state discrepancy in math anxiety in influencing students' reports on trait anxiety measures more so than on state anxiety measures. For this reason, students' endorsement of a math-related gender stereotype is assumed to be an additional significant predictor of the trait-state discrepancy, with the effects of this stereotype expected to differ for males as compared to females. As the stereotype favors boys, girls who endorse the stereotype should show a higher trait-state discrepancy in math anxiety. For boys, however, this relation should be the inverse: Boys who more strongly endorse this stereotype should report lower trait anxiety resulting in a smaller trait-state math anxiety discrepancy.

The Present Research

Following from recent findings on potential moderators of the discrepancy between trait and state emotion measures, our study aimed to examine an additional predictor of this trait-state discrepancy in the context of gender differences in math anxiety. Assuming that trait measures reflect individuals' *beliefs* about emotions, whereas state measures are assumed to better reflect individuals' *actual* emotions, the trait-state discrepancy can be understood to indicate the extent to which generalized perceptions of one's emotions differ from one's real-life and *in-situ* emotional experiences. It was expected that study findings would replicate previous study (Goetz et al., 2013) with gender differences in trait math anxiety as compared to state math anxiety being moderated by self-concept levels. As higher levels of perceived control have consistently been found to predict lower anxiety (Pekrun, 2006), students' with higher self-concepts were similarly expected to report lower trait anxiety levels, resulting in a lower trait-state discrepancy.

Additionally, the present study examined students' endorsement of a math-related gender stereotype as a predictor of this trait-state discrepancy. It was assumed that higher levels of stereotype endorsement would bias girls' trait self-reports differently than those for boys, given the negative performance implications of this stereotype for girls as opposed to the positive implications for boys. It was therefore anticipated that girls' trait-state discrepancy in math anxiety would be significantly higher than the trait-state discrepancy observed for boys.

To summarize, based on the results of Goetz et al. (2013), gender differences were expected in mathematics anxiety on trait-oriented self-report measures but not on state assessments during mathematics instruction (replication; Hypothesis 1). We further expected to find a previously observed discrepancy in trait vs. state assessments, with this discrepancy explained to a significant extent by students' mathematics self-concept (replication; Hypothesis 2). Additionally, students' endorsement of a mathematics-related gender stereotype was expected to correspond with a stronger trait-state discrepancy for females, with males who endorsed the stereotype showing lower discrepancy levels (extension; Hypothesis 3).

Material and Methods

Ethical Statement

Prior to participating in the study, the teachers, students, and parents (depending on school regulations) were informed about study contents and procedure. Confidentiality of data was guaranteed and participation was voluntarily such that withdrawal from the study was possible at any time. Data were collected confidentially and all information that could link individual participants to their results was destroyed before analyzing the data.

Participants and Procedure

German students ($N = 755$; 55.1 % female) from 42 classes of grades 9 and 10 ($M_{age} = 15.7$, $SD = 0.72$) of the highest academic track (Gymnasium, about one third of the total student population; Federal Statistical Office, 2015) participated in a diary study in the domain of mathematics. Students completed an initial paper-and-pencil questionnaire including trait measures of anxiety and related constructs (e.g., mathematics self-concept), as well as demographic items, administered by trained experimenters. Students subsequently participated in a 2–3-week study period during which they completed self-report measures addressing the study variables after each mathematics lesson as part of a short questionnaire. This protocol resulted in $N = 6207$ entries in the standardized diary with a mean of $M = 8.22$ entries per student. Students who rated only one lesson, or completed more than one standardized diary questionnaire per lesson, were excluded from the analyses (resulting in an exclusion of 5 students).

Trait Variables

To allow for trait and state anxiety ratings to be comparable, *trait mathematics anxiety* was assessed using two items obtained from a larger five-item scale (based on PALMA; Pekrun et al., 2007) that were formulated in parallel to the state assessment (e.g., "During mathematics instruction I often feel anxious"). The two items had satisfactory reliability (trait questionnaire: Spearman-Brown $\rho = 0.73$). The anxiety score summing across the two items was highly correlated with the original five-item scale ($r = 0.91$). Although assessing constructs with more items may be preferable with respect to reliability and validity, empirical evidence nonetheless suggests that measures having fewer items can be sufficiently valid (Gogol et al., 2014). *Self-concept in mathematics* was assessed using three items from the Self Description Questionnaire II (SDQ; Marsh, 1990; $\alpha = 0.88$; e.g., Mathematics is one of my best subjects), and students' endorsement of the *gender stereotype* ("Math is a male domain") was assessed using a single-item measure (adapted from Fennema and Sherman, 1977; Hyde et al., 1990). Trait mathematics anxiety items, self-concept items, and stereotype endorsement were rated on a five-point Likert scale ranging from 1= *strongly disagree* to 5= *strongly agree*.

State Anxiety

State mathematics anxiety (Spearman-Brown $\rho = 0.71$) was assessed using two items formulated in parallel to the trait mathematics anxiety items with respect to both phrasing and response format (e.g., "In this lesson I felt anxious"; 1 = *strongly disagree* to 5 = *strongly agree*). The parallel formulation of the trait and state measures ensured the comparability of anxiety levels required to examine our research question regarding potential trait-state discrepancies.

Statistical Analyses

Study data were analyzed with hierarchical linear modeling to account for multiple measurement points per student and students nested in classes (three levels). First, we combined the anxiety measures (trait and state) to assess them as a single dependent variable in the hierarchical linear regression models. To separate the trait from the state anxiety measures, we created a dichotomous dummy variable representing the method used to assess students' anxiety ("*Trait*": 0 = state, 1 = trait). In the multilevel regression models, the effect of this dummy variable can be interpreted as the magnitude of the difference between trait self-reports vs. state self-reports of anxiety: the trait-state discrepancy. To test the predictive validity of self-concept (Model 1) and gender stereotype endorsement (Model 2) of this discrepancy in girls and boys, we sequentially introduced the two variables (z-standardized) in the hierarchical linear models resulting in the following model equations.

Model 1 multilevel equation:

$$Y_{\mathrm{ijk}}[\text{Emotion value } i \text{ of student } j \text{ in class } k] = \gamma_{000} + \gamma_{100}(\text{Trait}) + \gamma_{010}(z\text{Self-concept}) + \gamma_{110}(z\text{Self-concept} * \text{Trait}) + \mathrm{r}_0 + \mathrm{r}_1(\text{Trait}) + \mathrm{u}_{00} + \mathrm{e}$$

Model 2 multilevel equation (notation as in **Table 2**):

$$Y_{\mathrm{ijk}}[\text{Emotion value } i \text{ of student } j \text{ in class } k] = \gamma_{000} + \gamma_{100}(\text{Trait}) + \gamma_{020}(z\text{Stereotype endorsement}) + \gamma_{120}(z\text{Stereotype endorsement} * \text{Trait}) + \mathrm{r}_0 + r_1(\text{Trait}) + \mathrm{u}_{00} + \mathrm{e}$$

In the multilevel models, self-concept and stereotype endorsement each function as a predictor of the slope of the Trait dummy variable (slope-as-outcome model) resulting in a cross-level interaction between Level 1 and Level 2 (Self-concept × Trait interaction; $\gamma_{110}$and Stereotype endorsement × Trait interaction; γ_{120}). The magnitude of these interaction terms therefore indicates the effect of self-concept or stereotype endorsement on the trait-state discrepancy, respectively. Positive effects indicate that higher self-concept/stereotype values are associated with greater discrepancies between trait and state assessments, whereas negative effects indicate smaller discrepancies. For the sake of completeness, self-concept and stereotype endorsement were both included in each model as a predictor of the intercept (γ_{010}). These effects however, were not a primary concern with respect to our study hypotheses.

Additionally, our analyses included both self-concept and gender stereotype endorsement as predictors in a single model (Model 3):

$$Y_{ijk}[\text{Emotion value } i \text{ of student } j \text{ in class } k] = \gamma_{000} + \gamma_{100}(\text{Trait}) + \gamma_{010}(z\text{Self-concept}) + \gamma_{020}(z\text{Stereotype endorsement}) + \gamma_{110}(z\text{Self-concept} * \text{Trait}) + \gamma_{120}(z\text{Stereotype endorsement} * \text{Trait}) + \gamma_{130}(z\text{Self-concept} * z\text{Stereotype endorsement} * \text{Trait}) + \mathrm{r}_0 + \mathrm{r}_1(\text{Trait}) + \mathrm{u}_{00} + \mathrm{e}$$

As we were primarily interested in the strength of the effects of the predictors on the trait-state discrepancy in math anxiety, that for stereotype endorsement were assumed to be reversed depending on a student's gender, Models 1–3 were analyzed separately for boys and girls (see Supplementary Material for hierarchical linear regression models for complete sample).

Results

Descriptives

The intraclass correlation coefficient (with respect to Levels 1 and 2) for the state anxiety measures was ICC(1) = 0.32

for female students and ICC(1) = 0.34 for male students. In addition, we calculated the ICC(2) that can be interpreted as a reliability measure of the aggregated state value (Lüdtke et al., 2006). The ICC(2) was 0.79 for girls and 0.81 for boys, indicating sufficient reliability for the aggregated state values. To examine our research questions (Hypothesis 1), mean-level differences were evaluated in the first step, showing gender differences in mathematics anxiety for trait anxiety (Cohen's $d = -0.12$) but not for state anxiety measures (see **Table 1**). Furthermore, male and female students were found to differ significantly in their math-related self-concepts, with boys reporting higher self-concept levels. Males were also found to more strongly endorse the math gender stereotype. The correlation between math self-concept and gender stereotype endorsement was $r = -0.36$ for girls and $r = 0.18$ for boys.

Main Analyses

For the main analyses, hierarchical linear models comprising 3 levels (measurement points at Level 1, students at Level 2, and classes at Level 3) were calculated to evaluate Hypotheses 2 and 3 (see **Table 2**). Analyses were conducted separately for each gender to more explicitly evaluate the anticipated differential effects for girls vs. boys.

Results indicated a significant trait-state discrepancy for girls ($\gamma_{100} = 0.22, p < 0.01$) that was not significant for boys ($\gamma_{100} = 0.07$, *ns*). As stated in Hypothesis 2, self-concept (Model 1) significantly and negatively predicted the trait-state discrepancy for girls ($\gamma_{110} = -0.29, p < 0.001$) as well as boys ($\gamma_{110} = -0.25, p < 0.001$). However, gender stereotype endorsement (GSE; Model 2) was found to differentially predict the trait-state discrepancy based on gender as stated in Hypothesis 3: This discrepancy was positively predicted by GSE for girls ($\gamma_{120} = 0.21, p < 0.001$), whereas for boys the effect of GSE was negative and marginally significant ($\gamma_{120} = -0.09, p = 0.05$).

When introducing both predictors to the model (Model 3), self-concept ($\gamma_{110} = -0.25, p < 0.001$) and GSE ($\gamma_{120} = 0.12, p < 0.05$) were both found to significantly predict the trait-state discrepancy for girls. For males, self-concept continued to be a significant predictor of the trait-state discrepancy ($\gamma_{110} = -0.25, p < 0.001$) but GSE was no longer a significant predictor ($\gamma_{120} = -0.04$, *ns*). For the sake of completeness, an additional interaction term between self-concept and gender stereotype endorsement was evaluated in a last step, but was not reported in the table as it did not significantly predict the trait-state discrepancy for girls or boys.

TABLE 1 | Descriptive statistics and mean level differences.

Scales	Girls		Boys		*t*-value	Effect size *d*
	M	*SD*	*M*	*SD*		
Anxiety-Trait	1.87	0.90	1.72	0.84	−2.32*	−0.12
Anxiety-State	1.65	0.84	1.64	0.81	−0.32	−0.01
Self-concept	2.86	1.18	3.26	1.15	5.19***	0.24
Stereotype Endorsement	1.76	1.14	2.12	1.24	4.39***	0.21

Positive t-values reflect higher scores for boys. For multi-item measures, scale values were divided by the number of items. n = 416 girls, n = 339 boys.
**p < 0.05, ***p < 0.001.*

Discussion

The aim of the present study was to shed light on gender differences in students' trait vs. state math anxiety. Furthermore, this study examined additional variables that were expected to contribute to the discrepancy between students' perceptions of trait math anxiety and their state math anxiety experiences in evaluating the effects of both students' self-concept and endorsement of a math-related gender stereotype as moderators of the trait-state discrepancy. Our study results replicate previous findings (Goetz et al., 2013) in showing girls to report higher levels of math anxiety relative to boys on trait assessments but not on state assessments of math anxiety with gender differences in trait anxiety being small in terms of effect sizes, but still significant.

Furthermore, self-concept negatively predicted the trait-state discrepancy as in previous studies (Goetz et al., 2013; Bieg et al., 2014), with our results additionally showing students' endorsement of a math-related gender stereotype to predict the trait-state discrepancy for female students. Girls who believed mathematics to be a male domain showed a larger discrepancy between their trait and state anxiety levels, with retrospective trait self-reports of anxiety being significantly higher than the state levels reported during actual math classes. This finding is in line with the assumption that gender stereotypes more strongly bias trait self-report measures than state measures (Robinson and Clore, 2002).

Our models also showed both self-concept and gender stereotype endorsement to predict trait-state discrepancy in female students when evaluated simultaneously. However, results showed the effect of stereotype endorsement to diminish when self-concept was introduced (see Model 3), suggesting that stereotype endorsement and self-concept are not entirely independent concepts. Nonetheless, it is important to note that stereotype endorsement was found to predict trait-state discrepancy over and above the effects of self-concept specifically for girls, highlighting the unique detrimental influence of these stereotyped mathematics beliefs on retrospective accounts of math anxiety primarily for female students.

Compared to female students, males were found to hold more stereotyped views of mathematics (see Hyde et al., 1990). Additionally, the effect of stereotype endorsement was inverted and marginally significant for male students, suggesting a tendency for male students who endorse the math-related gender stereotype to have lower trait-state discrepancies in their math anxiety. The negative implications of this mathematics-related gender stereotype for girls, and potential positive connotations for boys (cf. Steffens and Jelenec, 2011), confirm the expected pattern of results in showing a stronger overestimation of trait anxiety as compared to state anxiety for girls than for boys. In contrast, a strong mathematics self-concept, appears to serve

TABLE 2 | Hierarchical linear regression models with anxiety as dependent variable.

	Girls			Boys		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
LEVEL 1						
Intercept (γ_{000})	1.68*** (0.04)	1.68*** (0.04)	1.68*** (0.04)	1.67*** (0.04)	1.66*** (0.04)	1.67*** (0.04)
Trait (γ_{100})	0.22*** (0.04)	0.22*** (0.05)	0.22*** (0.04)	0.07 (0.05)	0.06 (0.05)	0.07 (0.05)
LEVEL 2						
Self-concept (γ_{010})	−0.13*** (0.03)		−0.10** (0.03)	−0.17*** (0.03)		−0.18*** (0.03)
Stereotype Endorsement [GSE] (γ_{020})		0.11*** (0.03)	0.07* (0.03)		0.04 (0.03)	0.07* (0.03)
Self-concept × GSE (γ_{030})						
CROSS-LEVEL INTERACTIONS L1–L2						
Trait × Self-concept (γ_{110})	−0.29*** (0.04)		−0.25*** (0.04)	−0.25*** (0.04)		−0.25*** (0.04)
Trait × GSE (γ_{120})		0.21*** (0.05)	0.12* (0.05)		−0.09+ (0.04)	−0.04 (0.04)
VARIANCE COMPONENTS						
Within-student (L1) variance (σ^2)	0.455	0.455	0.455	0.408	0.408	0.408
Intercept (L2) variance (τ_{00})	0.202	0.206	0.198	0.185	0.217	0.182
Slope (L2) variance (τ_{11})	0.047	0.090	0.034	0.045	0.102	0.043
Intercept-slope (L2) covariance (τ_{01})	−0.060	−0.043	−0.066	−0.064	−0.019	−0.062
Intercept (L3) variance	0.035	0.036	0.033	0.036	0.026	0.033
Explanatory power	0.649	0.328	0.746	0.583	0.056	0.602

Unstandardized b coefficients are shown. Trait: 0 = state, 1 = trait; GSE = gender stereotype endorsement; female sample: $N_{Level\ 1} = 3432$; $N_{Level\ 2} = 416$; $N_{Level\ 3} = 42$; male sample: $N_{Level\ 1} = 2775$; $N_{Level\ 2} = 339$; $N_{Level\ 3} = 42$. Explanatory power refers to the proportion of slope variance explained by the L2 predictors (Aguinis et al., 2013). The slope variance of the model in which no cross-level interactions are included was $\tau_{11} = 0.134$ for female sample and $\tau_{11} = 0.108$ for male sample.
$^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^+p < 0.10$.

a protective function for girls, particularly when performance-related gender stereotypes threaten their self-perceptions and emotional well-being in this domain. To summarize, our study findings show gender stereotype endorsement to increase the discrepancy between girls' assumed anxiety as compared to their actual anxiety levels (state anxiety) with endorsement of this stereotype found instead to diminish the trait-state discrepancy for boys—enhancing their self-perceptions regarding mathematics (Kurtz-Costes et al., 2008).

As mentioned above, the effect of stereotype endorsement was found to be weaker when self-concept was included as a second predictor—a finding consistent with previous research indicating a substantial degree of shared variance between math-related gender stereotypes and self-concepts in the domain of mathematics (Schmader et al., 2004; Kurtz-Costes et al., 2008). Regarding the direction of relationship between these constructs, gender stereotype endorsement may represent one reason why girls have lower self-concepts despite similar performance relative to boys. However, it is also possible that explicitly asking students about gender stereotypes may prompt them to draw conclusions based on their self-concepts in mathematics about how applicable these stereotypes are to themselves as a male or female student. Although the endorsement of the math-related gender stereotype is lower in female as compared to male students, our findings suggest that stereotype endorsement nonetheless has quite a negative effect on girls' trait anxiety ratings and perhaps also their attitudes regarding mathematics.

Concerning the study limitations, although the study findings suggest that state reports may be better able than trait questionnaires to capture emotions as they are experienced in daily life (Bolger et al., 2003), they nonetheless remain self-report measures and may produce different results as compared to other methods (e.g., behavioral observation, biometric indicators). Additionally, stereotype endorsement was assessed by use of a single straightforward item ("Mathematics is a male domain"). Future studies are recommended to replicate our findings with multi-item measures and to explore more specific elements of gender stereotypes, for example, with respect to the perceived value of the domain, possible careers afforded by math training, or the perceived proportion of female participation of the workforce in math domains (see Forgasz et al., 2004). Because of the mentioned limitations of self-reports and the tendency to deny beliefs in stereotypes when directly asked (Greenwald and Banaji, 1995), future studies could assess stereotype endorsement by the use of implicit measures (see Steffens et al., 2010). It can be assumed that the effect of implicitly measured gender-stereotype endorsement as predictor of the trait-state discrepancy may be even more pronounced. Our study sample was also limited to 9th and 10th graders in the highest track of the German school system (Gymnasium). Although these students typically represent those who subsequently enroll in university and obtain professional occupations with high responsibility, future studies are recommended to replicate our findings with a broader sample of students.

Finally, despite the study emphasis on measure-related differences in math anxiety for girls, it is critical to not overlook the importance of one's self-concept in mathematics as a predictor of the trait-state discrepancy in math anxiety for boys, especially those with lower self-concept levels. Thus, in addition to the study findings suggesting continued efforts to counteract the persistence of gender stereotypes to improve math anxiety for girls, these findings also warrant renewed interest in efforts to enhance self-concept beliefs for all students regarding mathematics given the significant and consistent benefits observed for both girls and boys in this domain.

In conclusion, these findings show an alarming effect of stereotype endorsement for girls who, due to inaccurate beliefs in gender differences in math ability, are at risk of believing they are more anxious than they report feeling in mathematics domains. These results therefore underscore the importance of initiatives on the part of schools, teachers, and parents to address and counteract gender stereotypes that may, in turn, help to correct the underrepresentation of females in mathematics-related careers.

Supplementary Material

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01404

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 30 November 2015
doi: 10.3389/fpsyg.2015.01833

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Math Anxiety Assessment with the *Abbreviated Math Anxiety Scale:* Applicability and Usefulness: Insights from the Polish Adaptation

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Math anxiety has an important impact on mathematical development and performance. However, although math anxiety is supposed to be a transcultural trait, assessment instruments are scarce and are validated mainly for Western cultures so far. Therefore, we aimed at examining the transcultural generality of math anxiety by a thorough investigation of the validity of math anxiety assessment in Eastern Europe. We investigated the validity and reliability of a Polish adaptation of the *Abbreviated Math Anxiety Scale* (AMAS), known to have very good psychometric characteristics in its original, American-English version as well as in its Italian and Iranian adaptations. We also observed high reliability, both for internal consistency and test-retest stability of the AMAS in the Polish sample. The results also show very good construct, convergent and discriminant validity: The factorial structure in Polish adult participants ($n = 857$) was very similar to the one previously found in other samples; AMAS scores correlated moderately in expected directions with state and trait anxiety, self-assessed math achievement and skill as well temperamental traits of emotional reactivity, briskness, endurance, and perseverance. Average scores obtained by participants as well as gender differences and correlations with external measures were also similar across cultures. Beyond the cultural comparison, we used path model analyses to show that math anxiety relates to math grades and self-competence when controlling for trait anxiety. The current study shows transcultural validity of math anxiety assessment with the AMAS.

Keywords: AMAS, math anxiety, anxiety, confirmatory factor analysis, cross-cultural studies, healthy adults

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: 15 July 2015
Accepted: 12 November 2015
Published: 30 November 2015

Citation:
Cipora K, Szczygieł M, Willmes K and Nuerk H-C (2015) Math Anxiety Assessment with the Abbreviated Math Anxiety Scale: Applicability and Usefulness: Insights from the Polish Adaptation. Front. Psychol. 6:1833. doi: 10.3389/fpsyg.2015.01833

INTRODUCTION

Definition and Societal Importance

Math underachievement and its broad social and personal consequences attract increasing attention from both scientific investigation and educational policy (e.g., OECD, 2010). It was already known in the 1970's that intelligence accounts for only 50% of the variance in math performance (see Suinn and Edwards, 1982). Math anxiety is considered to be one important factor contributing to individual math achievement. Interestingly, in past decades extensive research on this phenomenon was conducted mostly in the United States and Great Britain. Recently, the math anxiety construct has received more attention in other countries (see, e.g., Krinzinger et al., 2009). Recent developments in studies on math anxiety are reviewed by Suárez-Pellicioni et al. (2015). Nevertheless, we do not know how universal construct validities and psychometric properties of the mostly English studies are, especially as regards Eastern Europe, since such data are as of yet lacking. Therefore, in this study we examined the Polish adaptation of the *Abbreviated Math Anxiety Scale* (AMAS; Hopko et al., 2003).

The term math anxiety refers to negative states related to math and mathematical situations (for definition, history, and consequences see Ashcraft and Ridley, 2005). This very general definition can be expanded so that math anxiety refers to a wide range of negative emotional states that accompany an individual when struggling with math in different situations. These emotional responses vary from apprehension to fear and dread. These situations may involve everyday activities, in which an individual has to deal with numbers (e.g., financial transactions) as well as academic matters. Math anxiety leads to cognitive (e.g., worrisome thoughts) and behavioral (avoidance) consequences (see: Krinzinger et al., 2009 for comparison). Interestingly, Faust (1992; see Ashcraft and Ridley, 2005) claims that math anxiety meets the criteria of genuine phobia. It is therefore widely accepted that math anxiety is different from other forms of anxiety (see Suárez-Pellicioni et al., 2015). The independence of math anxiety from other possibly related constructs will be further discussed.

Math Anxiety and its Relations to Other Cognitive and Personality Variables

Importantly, math anxiety cannot be reduced to poor math performance, since the differences in math performance between high and low math anxious individuals depend largely on math testing conditions (Ashcraft and Ridley, 2005). Anxiety responses already appear when an individual is expecting to face mathematical problems (Lyons and Beilock, 2012). Therefore, measurement of math achievement itself may be compromised by math anxiety. The relationship between math achievement and math anxiety has been the subject of numerous studies summarized in a meta-analysis by Ma (1999). The average correlation between math anxiety and math grades was −0.27. The association between math anxiety and math performance, however, seems to be limited to areas of math with a strong involvement of numbers (e.g., Vukovic et al., 2013).

Besides performance measures, math anxiety also correlates with a number of personality constructs, providing some insights into its convergent and divergent validity. Ashcraft and Ridley (2005, p. 317, see also Ashcraft and Moore, 2009) give a summary of correlation coefficients between math anxiety and several other variables. It is based on two meta-analyses by Hembree (1990) and Ma (1999). If not stated explicitly, the data are taken from those meta-analyses. Here we discuss only correlations that are relevant for the purpose of the presented study.

In general, math anxiety correlates moderately with other forms of anxiety ($r \approx 0.40$), apart from test anxiety in which correlations are quite strong. Namely, correlations between several measures of math anxiety are considerably higher than correlations between measures of math anxiety and measures of other types of anxiety, thereby suggesting discriminant validity of the construct. This pattern of correlations is present both in children and in adults. Specific self-concepts (i.e., math self-concept and math self-efficacy) are also related to math anxiety. Math self-efficacy is defined as perceived ability to solve pure and applied math problems, whereas the term math self-concept denotes perceived competence in math (OECD, 2013). The correlations between math self-concept and math self-efficacy are extremely high (often above 0.90) which means that these constructs are hardly distinguishable from each other both practically and theoretically (Lee, 2009 for discussion). Nevertheless, those concepts were distinguished in 33 of 41 countries involved in the PISA study. The relation between these concepts and math achievement is also similar to the relation between math anxiety and math achievement (Lee, 2009).

In sum, math anxiety is correlated both with cognitive measures like math performance as well as with personality measures like state and trait anxiety, test anxiety as well as self-concept and self-efficiency in math.

Short-term Effects of Math Anxiety

Apart from long-term consequences of math anxiety, several short-term effects have been described. First of all, math anxiety may lead to so-called local avoidance. Highly math anxious individuals, when faced with math problem, feel uncomfortable and want to terminate this anxiety-evoking situation. This often leads to sacrificing accuracy for speed (i.e., random or unchecked answers are given; see Ashcraft and Ridley, 2005). Moreover, several cognitive consequences of math anxiety were described. First of all, anxiety reduces working memory capacity, which leads to decrements in performance (Ashcraft and Krause, 2007; see also Suárez-Pellicioni et al., 2015, for review). This is in line with general claims on how anxiety impairs cognition (see: Eysenck and Calvo, 1992). Solving math problems requires working memory capacities of storing, updating intermediate results and performing calculations. However, recent developments indicate that the relation between anxiety and working memory capacity is more complex. Individuals having less working memory capacity show deficits in inhibiting emotional responses (Hofmann et al., 2012). This aspect is extensively discussed by Trezise and Reeve (2014), who also point out that several patterns of working memory capacity and worry are less stable over time than others. Namely in some individuals, WM capacity and perceived level of worry change over measurements, whereas in other individuals they remain stable over time. Most dynamic changes were observed in individuals, who scored high in worry and in working memory in the initial test, whereas results were most stable in individuals, who scored low in worry and high in working memory capacity. These changes may also be associated with temporal fluctuations in math problem solving performance. Importantly, decrements in performance may be associated with tiredness, even within 1 day. Similarly Chuderski (2015) shows that the relation between WM capacity and anxiety is not present in high fluid intelligence individuals.

In sum, math anxiety is not only related to personality traits and long-term arithmetic skill, but also impairs short-term functioning in mathematical examination situations. However, pattern of these short-term relationships may differ across individuals.

Gender Differences

Female individuals—both adults and children—tend to reveal higher levels of math anxiety. Female individuals having the same cognitive capacities perform worse on math tests because their performance is compromised by math anxiety (Devine et al., 2012). Gender differences in math anxiety were also found in Great Britain (Hunt et al., 2011). On the other hand, Ma (1999) showed that there is no gender difference in the correlation between math anxiety and math achievement. Math anxiety was also shown to be more stable over time in female compared to male individuals. On the other hand, in male individuals, the relationship between past math achievement and later math anxiety is more pronounced (Ma and Xu, 2004). It is important to note that there are also studies reporting no gender differences or even higher Math anxiety in male participants (see: Devine et al., 2012 for a short review). Results of PISA 2012 study (OECD, 2013) show that in vast majority of OECD countries, averaged effect size of gender difference is small but meaningful ($d = 0.30$). In Polish adolescents the effect size can be considered as very small ($d = 0.11$). Similar differences were also observed in case of related constructs, namely math self-efficacy and math self-concept. As regards math self-efficacy, effect size averaged across OECD countries was 0.34 in favor of boys. This gender difference in Polish adolescents was very small ($d = 0.14$). In case of math self-concept the averaged effect size was 0.36. Again in Poland it was smaller but this time meaningful ($d = 0.22$).

In sum, gender differences in math anxiety as well as other, related concepts are present in most cultures. Female individuals (both adolescents and adults) report stronger math anxiety. Furthermore, they feel less confident when struggling with math problems. These differences are also present in Polish adolescents, however its size is rather small.

Cultural Differences and Similarities

The vast majority of research on math anxiety was conducted in the US. Nevertheless, some studies from other countries (mostly Western European and Eastern Asia) are also available. The meta-analysis performed by Ma (1999) suggests that there are no substantial cross-cultural differences in math anxiety. Nevertheless, several individual studies indicate such differences. E.g., Engelhard (1990) shows that Thai students reveal lower levels of math anxiety than their American peers.

Although the amount of research conducted outside the US is relatively small, more recent studies suggest that cultural differences are rather small or non-existent. Math anxiety was reliably measured in Britain (Hunt et al., 2011) as well. The questionnaire used in the study, the *Mathematics Anxiety Scale-UK* (MAS-UK) was adapted from the American original (MAS) to British conditions by eliminating items that were not easily understood by British English speakers. Several items were also added which refer to popular usage of math in British everyday life (e.g., playing darts). The structure of math anxiety was similar in the UK and in the US. Wood et al. (2012) also observed that the structure of math anxiety in school children (second and third graders) was the same in German and Brazilian samples. This result is particularly interesting, since the data come from two very different cultures. Moreover, German and Brazilian children differed considerably in math achievement as measured in the PISA program. Finally, in a study by Ho et al. (2000) the structure of math anxiety was found to be similar in American, Chinese and Taiwanese students. In this study, the two-componential structure of math anxiety was investigated (affective and cognitive aspects). The affective component seems to be consistently related to math achievement. The relations between the cognitive component of math anxiety and math achievement are more inconsistent across cultures.

One large-scale attempt to evaluate math anxiety across different countries was undertaken for data collected in the PISA 2003 program (Lee, 2009). The data was collected in 41 countries. The correlations between the PISA math score and math anxiety varied from about −0.50 (in Denmark, Norway and Poland) to about −0.15 (in Japan, Thailand and Indonesia). In most cases the correlation varied between −0.3 and −0.4 (Lee, 2009, see Table 7 there). Nevertheless, the math anxiety measure was established by means of a factor analysis of the PISA questionnaire data itself. It eventually comprised responses to five items referring to (1) getting nervous when solving mathematical problems; (2) tension when doing math homework; (3) worry that math classes will be too difficult; (4) worry of getting poor math grades; (5) thinking of not being good in math. These items do not allow for the investigation of the structure of math anxiety and responses to some of them (e.g., worry of getting poor grades) may strongly depend on the cultural context. PISA 2003 showed that the correlation between math anxiety and performance in Poland was one of the highest in all countries involved in the programme ($r = -0.49$; Lee, 2009).

The recent PISA 2012 study (OECD, 2013) provided more insights into math anxiety and its relation to math scores and characteristics of math anxiety in Poland. First of all, the relationship between math anxiety and math performance did not change considerably and remained one of the strongest. However, Polish students scored slightly above PISA average in math and slightly below PISA average in math anxiety.

In summary, there were some, yet rather small differences between cultures. However, instruments differed between studies and sometimes (e.g., Hunt et al., 2011) instruments were even changed to adapt them to a certain culture. While this is understandable, it makes cross-cultural comparisons more difficult. Therefore, we will use the same assessment tools as previously examined in the US, Iran and Italy. This allows for a more direct comparison between these countries and Poland.

Is Math Anxiety a Homogenous Construct? Structure of Math Anxiety

So far, in this introduction, we have treated math anxiety as a homogenous construct. However, in general, it is claimed that there are at least two broad components of math anxiety, referring to the use of math in everyday life situations and being tested in math (e.g., Hopko, 2003). This two-factor structure was already proposed in research starting in the early 1970's (see: Suinn and Edwards, 1982). However, 3-factor structures (Alexander and Martray, 1989; Hunt et al., 2011) have also been proposed.

Importantly, there are also approaches that still assume a unidimensional structure of Math anxiety. Ashcraft (2002) claims that asking a single question on how math anxious an individual is, may be also a valuable way of math anxiety assessment (the results strongly correlate with results of psychometrically validated math anxiety measurement instruments). A similar approach was also taken in the PISA 2003 study (see Lee, 2009). Núñez-Peña et al. (2014) systematically tested the possibility of assessing math anxiety by using a single item measure called *Single Item Math Anxiety Scale* (SIMA). This instrument is characterized by satisfactory psychometric properties and seems to be an interesting alternative to longer math anxiety assessment instruments.

In sum, the factorial structure of math anxiety is still under debate and differs from author to author.

The Abbreviated Math Anxiety Scale (AMAS)

One of the most interesting instruments for investigating math anxiety, which will also be used in this study, was developed by Hopko et al. (2003). The AMAS is a nine-item questionnaire characterized by very good psychometric properties. The authors present a thorough psychometric evaluation of the AMAS, examining internal consistency, test-retest reliability and several validity measures.

Similar to previous scales, the AMAS total score is composed of two components (1) anxiety related to learning math (*Learning*) and (2) anxiety related to being tested in math (*Testing*). In the presented paper we focus on this questionnaire because of several reasons. First, the short form together with its very good psychometric properties makes it a very good tool for further research. It is suitable for testing both adults and school children (aged 11–16; Devine et al., 2012). Second, the administration of the AMAS takes <5 min and therefore, apart from studies focusing directly on math anxiety, it can easily be included in studies on numerical cognition.

The AMAS was successfully adapted to cultures largely differing from the US. Vahedi and Farrokhi (2011) studied the Iranian adaptation of AMAS, whereas Primi et al. (2014) presented its Italian adaptation. Both studies provided further evidence for the construct validity and reliability of this assessment tool. Results of these studies suggest that the AMAS is suitable for testing math anxiety in varied cultural and linguistic contexts. Furthermore, the factor structure of the AMAS remains invariant and did not show gender differences. Gyuris and Everingham (2011) administered a modified AMAS to Australian students. In the modified version two items about dealing with graphs were added and the item about the pop-quiz was modified stating that the quiz was not for credit. In general, the pattern of results followed the results obtained in the US study; nevertheless modifications introduced by the authors prevent direct comparisons. Convergent and discriminant validity of the AMAS was established by correlating its results with other math anxiety measures (e.g., sMARS; Hopko et al., 2003); test anxiety (e.g., TAI; Hopko et al., 2003; Primi et al., 2014); state and trait anxiety (e.g., STAI; Hopko et al., 2003); math attitudes, motivation to learn, etc… (Vahedi and Farrokhi, 2011; Primi et al., 2014); math grades (Gyuris et al., 2012). All these analyses revealed satisfactory validity indices. However, no measures of attitudes toward humanities were tested (as an indicator of discriminant validity). Furthermore, to the best of our knowledge, no measures of general personality/temperament were used in studies examining psychometric properties of the AMAS scale.

Properties of AMAS scale we reported above make it very useful math anxiety assessment tool for studies on numerical cognition. This is particularly important since sources of individual differences in several aspects of numerical processing are largely unknown (e.g., Cipora and Nuerk, 2013; Hoffmann et al., 2014a,b). There is recent evidence indicating a relationship between math anxiety and elementary numerical processing (e.g., Maloney et al., 2011). In some of those studies, the authors explicitly call for the inclusion of math anxiety as a covariate in studies on numerical cognition (Hoffmann et al., 2014b). The AMAS was already used in order to measure math anxiety in studies by Maloney et al. (2010), Maloney et al. (2011), Maloney et al. (2012), Hopko et al. (2005), and Devine et al. (2012). Furthermore, Maloney (2011) in her dissertation reports results of testing a large sample of college students (over 2000) with AMAS and providing further evidence for high reliability of the AMAS. The original version of the AMAS is freely available for research use from Derek Hopko's website.

Aim of the Present Study

In the present study, we aimed to investigate possible cultural differences and gender differences in math anxiety level and structure. In particular, we aimed to further evaluate the psychometric properties of the AMAS. The items of this questionnaire were in our opinion applicable to math-learning situations in Poland (so that in our opinion their content did not require changes as was necessary e.g., in the British adaptation of the US-American *Mathematics Anxiety Scale*; Hunt et al., 2011). However, principal applicability does not imply psychometric properties are the same across cultures—construct validity of the Big Five items for instance differs between cultures. Therefore, we focused on examining construct validity, reliability and both convergent and discriminant validity of the AMAS. Moreover, we compared results from a large-scale Polish sample to results described for the US and other countries mentioned above. Based on previous research with some other instruments, we expected that a similar pattern of results would be obtained for convergent and discriminant validity, as was presented in Hopko et al. (2003), as well as obtained in previous studies using other math anxiety measures (i.e., studies summarized by Ashcraft and Ridley, 2005). We also aimed at checking aspects of discriminant validity, assessing whether AMAS scores do not simply reflect general negative attitudes in the school environment.

Since there is no obvious reason to assume otherwise, we expected that the results for the AMAS obtained in the Polish sample would be similar to those obtained in samples from other linguistic and cultural backgrounds. This includes similarities in psychometric properties as well as average scores, but gender differences in that female individuals should exhibit higher math anxiety.

METHODS

Participants

Eight hundred and fifty-seven participants took part in the study. Six hundred and eighty-eight of them were female, 160 male and nine did not report their gender. Mean age was 21.6 (SD = 4.1) years and ranged from 18 to 49 years (based on information reported by 841 participants). Participants were students from six Polish universities located in three cities (Kraków, Wrocław, and Nowy Sącz). They studied in a wide range of faculties (psychology, education, law, philosophy, Polish literature, English literature, management and production engineering, medical physics, econometrics). Participation was voluntary. Assessment was done during university classes. The study was conducted in accordance with ethical standards of Jagiellonian Univerisity's Institute of Psychology. According to these regulations conducting questionnaire studies at the time the data was collected, explicit consent of Ethics Committee was not required. Questionnaires were distributed across the audience and the students were free to fill it or refrain from filling them (as well as not responding to questions they wished not to respond).

Materials

Math-related Measures

AMAS

Two trained psychologists (one of them was the first author) whose native language was Polish translated the original AMAS items from English into Polish independently from each other. Subsequently, the final Polish version of the item wordings was established after discussion between the first author (the first translator) and the second author (both of them are native Polish speakers). Thereafter, a trained psychologist, who was not familiar with the original items before, back translated items. Back-translated items were identical to the original ones except for one phrase (*pop quiz*) that was translated correctly semantically, but was not literally identical (*unannounced test*). Therefore, it was concluded that the translation was satisfactory.

The instructions were prepared in Polish as well. They stated that the participant will see some statements below which are related to learning math. He or she was asked to mark next to each statement the level of anxiety it evokes/would evoke in her/him. Similarly as in the original version, a 5-point Likert scale was used. Henceforth the theoretical range of AMAS score is from 9 to 45, in *Learning* scale it is from 5 to 25 and for *Testing* scale from 4 to 20. To make the AMAS consistent with the MAAA scale (described below), only low and high extremes were labeled (*mild anxiety* and *strong anxiety,* respectively). The AMAS was printed on DinA5 (148 × 210 mm) white paper sheets.

Math Ability, Achievement and Attitudes (MAAA)

This scale was developed for the purpose of this study. It was comprised of five parts. In the first part, participants were asked to assess their math ability on a 10-point Likert scale. There were four items on this scale (math in general, arithmetic, geometry and solving real life problems). The extremes of the scale were labeled *very bad* and *very good,* respectively.

In the second part, the participants were asked to mark their typical math grades. There were three items, each referring to one of the stages of obligatory education in Poland (1) elementary school (grades 1–6); (2) so called "gymnasium" (grades 7–9); (3) high school (grades 10–12/13 depending on high school type). At all these levels, math classes are an obligatory part of the curriculum. The participants used a scale compatible with the Polish grading system (i.e., from 1 to 6; 1 refers to the worst grade, 6 to the best grade). The extremes of the scale were marked with Polish verbal labels referring to the worst and the best mark respectively.

In the third part there were two items in which the participants marked how fast they get discouraged while solving a mathematical problem and when they have to write a difficult essay in humanities. The answers were again given using a 10-point Likert scale. The extremes (1 and 10) were marked with labels *I get discouraged very fast* and *I am very persistent,* respectively. In the fourth part with two items, the participants had to mark, how often they used some forbidden aid, while struggling with math problems and problems involving humanities. Similarly, the answers were given on a 10-point Likert scale with the extremes 1 and 10 labeled with *very often* and *I always work on my own*, respectively. In the fifth part comprising three items, participants marked how much they liked math, science and humanities. Responses were given using a 10-point Likert scale again with the extremes 1 and 10 marked with *I dislike very much* and *I like very much*, respectively. The MAAA was printed on a DinA4 sheet.

General Measures

Anxiety assessment

The Polish version of the State and Trait Anxiety Inventory (STAI) was used (Spielberger et al., 1970; Polish adaptation by Spielberger et al., 1987) to measure the level of state and trait anxiety. Reliabilities for the age groups 21–40 and 41–54 years, which are relevant for our sample characteristics, were 0.89–0.92 for STAI-X1 (state) and 0.82–0.90 for STAI-X2 (trait), depending on age group and gender (numerically lower reliabilities were found in the male group).

Temperament assessment

The *Formal Characteristics of Behavior—Temperament Inventory* (FCB-TI; Strelau and Zawadzki, 1993, 1995) questionnaire is based on the regulative theory of temperament by Strelau, who defines temperament as the "Expression of Energy Level and Temporal Features of the behavior" (Strelau, 2000, p. 164). The FCB-TI is comprised of 120 items with a *YES* and *NO* response format and assesses six temperament traits: "(1) Briskness (BR): tendency to react quickly, to keep a high tempo of performing activities, and to shift easily in responses to changes in the surroundings from one behavior or reaction to another. (2) Perseverance (PE): tendency to continue and to repeat behavior after cessation of the stimuli (situations) evoking the behavior. (3) Sensory Sensitivity (SS): ability to react to sensory stimuli of low stimulative value. (4) Emotional Reactivity (ER): tendency to react intensively to emotion generating stimuli, expressed in high emotional sensitivity and in low emotional endurance. (5) Endurance (EN): ability to react adequately in situations demanding long-lasting or high stimulative activity and under intensive external stimulation. (6) Activity (AC): tendency to undertake behavior of high stimulative value or to supply, by means of behavior, strong stimulation from the surroundings." (Strelau and Zawadzki, 1995, p. 208). The FCB-TI has high validity. For instance, ER correlates (≈0.7) with neuroticism, and negatively (≈−0.3) with extraversion; PE correlates with neuroticism as well (≈0.6). BR correlates with extraversion (≈0.3), and negatively with neuroticism (≈ −0.4); EN correlates negatively with neuroticism (≈ −0.5) and positively with extraversion (≈0.2), all measured with Eysenck's EPQ-R questionnaire. Several other validity measures were reported by Strelau and Zawadzki (1995). The scales were also characterized by satisfactory reliabilities as measured with Cronbach alpha (BR = 0.77; PE = 0.79; SS = 0.73; ER = 0.82; EN = 0.85; AC = 0.84).

Design of the Study

AMAS Reliability

In the presented study we aimed at checking basic psychometric properties of the AMAS. Reliability of the AMAS was assessed in two ways.

First, we used Cronbach alpha as a measure of internal consistency. It was calculated both for the global AMAS score as well as for the scales proposed in the original paper by Hopko et al. (2003).

Despite great popularity in psychometrics, feasibility of the Cronbach alpha coefficient for estimating reliability of Likert type response data has been challenged. Cronbach alpha uses the inter-item correlation matrix in order to obtain an estimate of reliability. The Pearson correlation coefficient may be deflated when the assumption of continuity of the data is violated. This is the case in Likert-type responses. This leads to underestimates of reliability, especially when the response scale is short. Underestimation of reliability is even more severe when scales are comprised of a relatively small number of items (Yang and Green, 2011). Also, non-normal distributions of both true scores and error scores were shown to cause problems with the traditional alpha coefficient (Sheng and Sheng, 2012).

Using polychoric correlation instead of Pearson correlation in order to calculate the alpha coefficient is suggested as an alternative that takes into account that the observed data are not continuous *per se*, but are ordinal manifestations of a continuous latent construct of interest (Zumbo et al., 2007).

Second, we used the test-retest method (by means of Pearson correlations and intraclass correlations). A subsample of 110 participants (only psychology students) filled in the AMAS for a second time 4 months after the first administration. Both the global score and the subscales were analyzed.

Construct and Scale Validity

We assessed the validity of the AMAS in several ways. First, to examine whether the factor structure of the Polish version resembles the original AMAS, a confirmatory factor analysis was carried out. Additionally, an exploratory factor analysis was conducted (see Data Sheet 1). Additionally we conducted exploratory factor analysis for female and male participants separately to investigate whether the factor structure differs between genders. To establish convergent and divergent validity, we used several other measures: anxiety scales, MAAA items referring to math and the Emotional Reactivity scale of FCB-TI for convergent validity; the MAAA items referring to humanities, in order to demonstrate that the AMAS score does not reflect a general negative attitude toward school, as well as being easily discouraged or looking for external help when facing difficult problems, for discriminant validity. No direct predictions were drawn as regards other FCB-TI scales.

Differences in correlations of the AMAS score with other related measures, for which predictions had been derived, were tested for significance by comparing dependent correlation coefficients (Chen and Popovich, 2002).

Procedure

The data were collected in a group setting, mostly during lectures or seminars. The order of the questionnaires was as follows: AMAS, STAI (state scale first), MAAA scale and finally, FCB-TI. The sessions usually did not exceed 20 min, except for the sessions with the FCB-TI, because the temperament assessment took about 15 additional minutes. A short verbal instruction was given at the beginning. The non-obligatory character of the study was stressed. Participants were informed that anonymized data would be used for scientific purposes only. Participants were asked to read all instructions carefully. Not all participants were administered the state anxiety questionnaire as well as the FCB-TI. As mentioned above, questionnaires were administered during university lectures and seminars and therefore session time was constrained. For that reason we did not administer the FCB-TI to all participants. Temperamental traits measured with the FCB-TI are not supposed to be directly related to math anxiety. We decided to include state anxiety during the course of data collection, which—also because of time constraints—was not included from the onset of data collection. After the questionnaires were collected, a short debriefing was provided, explaining that we aimed to prepare a Polish version of the Math Anxiety questionnaire AMAS.

RESULTS

AMAS Descriptive Statistics

The average *AMAS total* score was 21.9 (SD = 6.6). The average score of the *Learning* scale was 8.3 (SD = 3.7), while for the *Testing* scale it was 13.6 (SD = 4.0). Average scores of the individual items are presented in **Table 1**. The total scores for the *Testing* and *Learning* scales were moderately correlated (0.49). Both scales strongly correlated with the total score (0.88 and 0.85 for *Testing* and *Learning* scales, respectively). In the *AMAS total*

TABLE 1 | Item analysis of the Polish adaptation of the AMAS questionnaire.

Item	Item description	Sub-scale	Descriptive statistics		Corrected item-total correlations*			CFA, squared multiple correlation	
			Mean score	*SD*	Total	Learning	Testing	Learning	Testing
1	Using tables	*L*	1.54	0.95	0.53	0.62	0.30	0.16	–
2	Test 1 day before	*T*	3.24	1.29	0.77	0.44	0.87	–	0.68
3	Watching teacher's work	*L*	1.64	0.96	0.66	0.76	0.39	0.36	–
4	Math exam	*T*	3.81	1.18	0.67	0.28	0.84	–	0.60
5	Homework	*T*	2.77	1.21	0.75	0.51	0.77	–	0.53
6	Attending lecture	*L*	1.71	1.07	0.65	0.80	0.35	0.49	–
7	Other student explaining Math	*L*	1.68	0.99	0.58	0.76	0.28	0.42	–
8	Pop quiz	*T*	3.79	1.19	0.71	0.38	0.82	–	0.59
9	New chapter	*L*	1.75	1.04	0.69	0.72	0.48	0.50	–
Sum								1.51	2.40

*The table includes descriptive statistics together with item-total correlations and squared multiple correlations from the confirmatory factor analysis. *p < 0.001.*

score female participants obtained significantly higher scores than male participants [$t_{(846)} = 6.64$; $p < 0.001$; $d = 0.61$]. Means for female and male participants were 22.6 (SD = 6.6) and 18.9 (SD = 6.7), respectively. Significant differences were present for both scales. For the *Learning* scale mean scores were 8.5 (SD = 3.7) and 7.6 (SD = 3.1) for female and male participants, respectively [$t_{(846)} = 2.75$; $p = 0.002$; $d = 0.25$]. For the *Testing* scale mean scores were 14.2 (SD = 3.9) and 11.3 (SD = 3.9) for female and male participants, respectively [$t_{(846)} = 8.55$; $p < 0.001$; $d = 0.75$].

We also tested whether AMAS scores differed between students who had math in their current curricula (math group; $n = 168$) and those who did not (non-math group; $n = 689$). As expected, the non-math group scored higher on the AMAS than the math group. For the *AMAS total* scores were 22.4 (SD = 6.8) and 19.8 (SD = 5.3) and the difference was significant [$t_{(855)} = 4.62$; $p < 0.001$; $d = 0.42$]. The difference was also significant for the *Learning* scale [$t_{(855)} = 3.50$; $p < 0.001$; $d = 0.32$] with means 8.5 (SD = 3.8) and 7.4 (SD = 3.0) respectively and for the *Testing* scale [$t_{(855)} = 4.42$; $p < 0.001$; $d = 0.39$] with means 13.9 (SD = 4.0) and 12.4 (SD = 3.6), respectively.

The distributions of results for the total score and the subscales are presented in **Figures 1A–C**. As can be seen in **Figure 1A**, the *AMAS total* score was close to a normal distribution (skewness = 0.54, SE = 0.08; kurtosis = 0.12, SE = 0.17; both estimates fall within ±2 range so that they can be considered as acceptable; George and Mallery, 2010), but the formal test (*Shapiro-Wilk* $_{857} = 0.98$; $p < 0.001$) indicated significant deviation from normality. The average score was slightly below the scale midpoint (which is 27). The *Learning* scale was strongly skewed (skewness = 1.51, SE = 0.08; kurtosis = 2.40, SE = 0.17; therefore especially skewness falls outside acceptable ±2 range). A formal test also indicated that the distribution deviated significantly from normality (*Shapiro-Wilk* $_{857} = 0.83$; $p < 0.001$). Over 230 participants achieved the minimal score, and the average score was substantially below the scale midpoint (which is 15). The distribution of the results of the *Testing* scale was closer to a normal distribution (skewness = −0.34, SE = 0.08; kurtosis = −0.70, SE = 0.17, with both estimates falling within acceptable ±2 range), with the average score close to the scale midpoint of 12. Nevertheless, the formal test again showed a significant deviation from a normal distribution (*Shapiro-Wilk* $_{857} = 0.97$; $p < 0.001$).

AMAS Reliability

Cronbach Alpha

First, internal consistency was estimated using the Cronbach alpha coefficient. The reliability estimate was 0.85, 0.78, and 0.84 for the *AMAS total*, the *Learning* scale and the *Testing* scale, respectively. The average inter-item correlation was 0.38, 0.42, and 0.57 for *AMAS total*, *Learning* scale, and *Testing* scale, respectively. The corrected item-total correlations with the total score as well as with total score for each scale are presented in **Table 1**.

Additionally, we checked whether there were considerable differences in reliability between mat and non-math groups. The *AMAS total* reliability for the non-math group was 0.85, whereas for the math group it was 0.79. Reliability for the *Learning* scale was 0.79 and 0.70 for the non-math and math groups, respectively. For the *Testing* scale the coefficients were 0.85 and 0.81, respectively.

Ordinal Alpha

To further explore the reliability of the AMAS, we additionally calculated ordinal Alpha coefficients using the procedure suggested by Gadermann et al. (2012). Ordinal alpha for the AMAS *total* scale was 0.88 for the *Learning* scale 0.84, and for the *Testing* scale 0.87. Ordinal alpha did not increase if any item was dropped; the only exception was an increase by 0.01 in the *Testing* score when item 5—*homework*—was dropped.

Test Retest Reliability

Subsequently, AMAS test-retest reliability was examined by administration of the AMAS to a subsample of 110 psychology

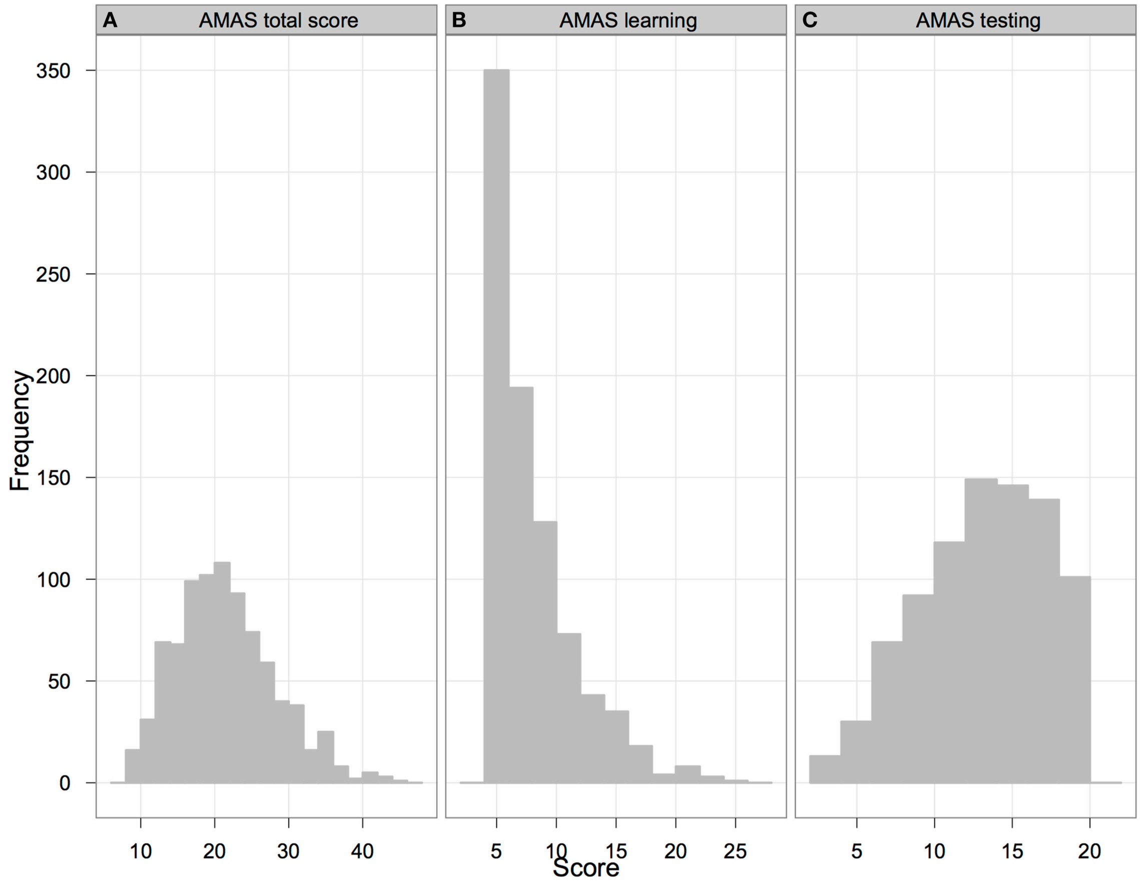

FIGURE 1 | Distribution of *AMAS total* (panel A) and scale totals (panels B and C for Learning and Testing scales respectively). The score-range for the *AMAS total* is from 9 to 45, for the *Learning* scale from 5 to 25, for the *Testing* scale from 4 to 20.

students 4 months after the initial testing. First, we compared means and variances in the initial testing of the retest subsample to other participants not taking the retest. Levene's test was used to check for variance equality. The difference in means was significant for the *AMAS total* 20.6 (SD = 5.6) and 22.1 (SD = 6.8) in the retest subsample and other participants respectively, $t_{(855)} = 2.15$; $p = 0.032$; $d = 0.23$. Variances did not differ between groups (Levene's test, $F = 2.63$; $p = 0.106$). The difference in mean *Learning* scale performance was significant as well, 7.3 (SD = 2.6) and 8.5 (SD = 3.8) for the retest subsample and other participants, respectively, $t_{(855)} = 4.17$; $p < 0.001$; $d = 0.36$. Variances differed as well (Levene's test, $F = 16.97$; $p < 0.001$). Contrarily, for the *Testing* scale the mean score did not differ between retest sample (13.4; SD = 3.8) and other participants (13.6; SD = 4.0); $t_{(855)} = 0.65$; $p = 0.515$; $d = 0.07$. There was no difference in variances (Levene's test, $F = 0.55$; $p = 0.457$).

Retest scores for *AMAS total*, *Learning* and *Testing* scales were 21.0 (SD = 5.3); 7.8 (SD = 2.5); and 13.2 (SD = 3.7), respectively. The differences in scores for *AMAS total* and *Testing* scale were not significant between the initial testing and the retest (p's > 0.45). For the *Learning* scale, the difference was significant [$t_{(109)} = -2.05$; $p = 0.042$].

Subsequently, test-retest reliabilities were estimated via Pearson correlations. These reliabilities were: 0.71, 0.59, 0.71 for the *AMAS total*, *Learning* scale, and *Testing* scale, respectively.

The observed floor effect in *Learning* scale as well as the lower variability in this scale in the retest subsample in the initial testing, most probably account for poor test-retest reliability of the *Learning* scale. Furthermore, a significant difference in *Learning* scale between the initial testing and the retest indicate that this reliability estimate must be taken with caution.

Pearson correlation is an estimate of test-retest reliability if two measurements are essentially tau-equivalent (i.e., the variance is identical and the true scores change only in a constant value that is identical for all participants (Ludbrook, 2002; Weir, 2005). Therefore, we additionally computed intraclass correlations (ICC) that take into account consistency of performance from test to retest and change in average performance of participants as a group over time (i.e., change in mean; Vaz et al., 2013). It is therefore more suited here since we observed significant difference in *Learning* scale between test and retest. We used the two-way random effects model with absolute agreement. In all instances ICCs (for single measures) were identical to the above Pearson correlations for the first two decimals. Therefore, differences in *Learning* scale were not substantial.

Factor Structure–Confirmatory Factor Analysis

The presented version of the AMAS questionnaire was an adaptation of an already established scale. Therefore, construct validity was analyzed by means of confirmatory factor analysis. We aimed at testing the structure of math anxiety and its components using structural equation modeling. The model was built in such a way that it matched the original factor structure of the AMAS (also found in an exploratory factor analysis—Data Sheet 1). It involved two correlated latent variables representing the *Learning* and *Testing* Math anxiety components. Items 1, 3, 6, 7, 9 were assumed to contribute to the *Learning* latent variable, whereas items 2, 4, 5, 8 were assumed to contribute to the *Testing* latent variable. We found that the multivariate normality assumption was violated (multivariate kurtosis = 25.90 < critical ratio = 26.94); therefore an asymptotically distribution-free (ADF) method was used. For the same reason, CMIN/DF measures of model fit are not reported, since they are sensitive to violations of the normality assumption (Bedyńska and Książek, 2012).

The model, together with standardized path coefficients, is presented in **Figure 2**. All parameter estimates were found to be significantly different from zero.

As can be seen in **Figure 2**, apart from Item 1 (*using tables*), all loadings are at acceptable levels (>0.60). Squared multiple correlations between items and the respective subscales are reported in **Table 1**. Apart from Item 1 (*using tables*), all values are close to or above 0.4. In general, the fit of the model was acceptable, but not perfect (RMSEA = 0.092; 90%-confidence interval 0.081–0.103; AGFI = 0.866).

Taking into consideration the loadings for item 5 (*homework*) on both scales, observed in exploratory factor analysis, an alternative structural model was tested with a path also from the *Learning* latent variable to this item. This is also justified from a theoretical point of view. Being given difficult homework involves both a learning situation and elements of being tested when the work is checked, usually in front of the class. This model had a more satisfactory fit (RMSEA = 0.075; 90%-confidence interval 0.064–0.087; AGFI = 0.905), suggesting that this item contributes to both factors. In the modified model, paths to this item were 0.42 and 0.39 for *Learning* and *Testing* scales respectively and the correlation between the latent variables decreased to 0.63.

AMAS Criterion Validity

As was stated in the predictions section, several correlational analyses were conducted in order to examine the convergent and discriminant validity of the AMAS. All respective data is presented in **Table 2**.

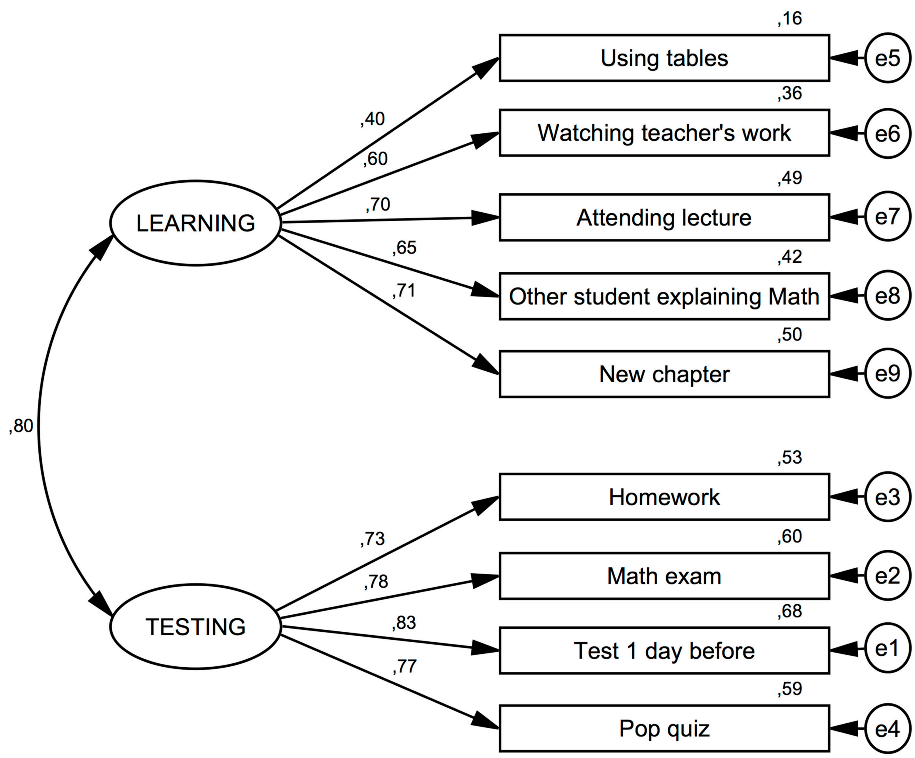

FIGURE 2 | Confirmatory Factor Analysis for the AMAS. Indices of model fit are provided and discussed in the main text. The results of the confirmatory factor analysis show that the internal structure of the Polish adaptation of the AMAS is similar to the structure found in the US-American sample. Standardized coefficients are provided for the structural equation model. Variables labeled with e1, e2 etc…denote the respective error terms.

TABLE 2 | Convergent and discriminant validity of the AMAS questionnaire.

Group	Measure	*n*	AMAS total	AMAS Learning	AMAS Testing
Self assessed math skill (MAAA)	Math skill	809	−0.50**	−0.36**	−0.49**
	Arithmetic skill	808	−0.47**	−0.36**	−0.45**
	Geometry skill	809	−0.43**	−0.34**	−0.41**
	Text problems skill	808	−0.44**	−0.31**	−0.44**
Self report of math scores during education (MAAA)	Typical grade–elementary school	809	−0.32**	−0.30**	−0.26**
	Typical grade–gymnasium	798	−0.39**	−0.32**	−0.35**
	Typical grade–high school	809	−0.38**	−0.28**	−0.36**
	Typical grade–average	810	−0.44**	−0.36**	−0.40**
Discouragement when solving problems (MAAA)	Discouragement–Math problem	810	−0.48**	−0.37**	−0.46**
	Discouragement–Essay	809	0.09*	0.05	0.10**
Non-allowed help usage (MAAA)	Non-allowed help–Math	808	−0.46**	−0.36**	−0.43**
	Non-allowed help–Humanities	802	0.06	0.03	0.07
Liking school subjects (MAAA)	I like Math	809	−0.50**	−0.36**	−0.50**
	I like Sciences	809	−0.32**	−0.23**	−0.32**
	I like Humanities	808	0.12**	0.08*	0.12**
Temperament (FCB-TI)	Sensory Sensitivity	130	0.13	0.15	0.09
	Emotional Reactivity	130	0.48**	0.35**	0.48**
	Perseverance	130	0.28**	0.21*	0.28**
	Activity	130	−0.03	0.03	−0.07
	Briskness	130	−0.27**	−0.16	−0.31**
	Endurance	130	−0.27**	−0.15	−0.30**
Anxiety (STAI)	State Anxiety	280	0.22**	0.18**	0.20**
	Trait anxiety	818	0.33**	0.22**	0.34**

Names of measurement instruments used are presented in parentheses in the first column. All correlations are reported with the respective sample size, which differs considerably in several cases. Significant correlations are marked with asterisks.
$^{**}p < 0.01$ (two tailed); $^{*}p < 0.05$ (two tailed).

For clarity of description we only present a simplified correlation matrix, in which only correlations between the AMAS scores with external measures are presented. The complete correlation matrix is presented in Data Sheet 2.

As can be seen in **Table 2**, the AMAS scores strongly correlated with self-assessed math skills: higher levels of math anxiety were associated with poorer self-assessed math competence. Visual inspection of scatterplots representing the relationship between the AMAS total score and average school grade and the AMAS total score and self-assessed math skill showed no departures from a linear relationship. It was also corroborated by inspection of the Lowess curves superimposed over the scatterplots. The same was true in case of both AMAS scales.

This negative correlation is present for all fields of math included in the scale. Interestingly, the relation was stronger for math skills in general than for geometry ($p < 0.001$). The AMAS scores correlated negatively with self-reported typical math scores at all levels of education. Participants with a higher level of math anxiety achieved worse grades (in the Polish system of school grades, numerically high grades correspond to good scores). Interestingly, when the correlation between the AMAS and self-assessed math skills was compared to the correlation between the AMAS and average school grade, the latter was significantly lower ($p = 0.015$). Hence, math anxiety is more strongly related to self-assessed skill than to school grades (but it correlates with both).

Moreover, participants showing higher levels of math anxiety reported getting discouraged faster when struggling with math problems. Interestingly, in the case of struggling with difficult essays, they perceived themselves to be more persistent. Here, the correlation with the AMAS was very small but positive. This correlation may be caused by several factors—highly math anxious participants prefer humanities because of better performance in the latter. On the other hand, participants might simply have contrasted their persistence in math and humanities and the latter seemed much higher to them. Higher math anxiety was associated with more use of non-allowed aids when struggling with math problems, but did not correlate with it in the case of humanities (all based on self-reports). Higher math anxiety was associated with less liking of math and science, but the correlation was significantly smaller in the case of science ($p < 0.001$). Contrarily, higher math anxiety was associated with more liking of humanities. Therefore, the AMAS score can neither be accounted for by general attitude toward school and school subjects nor by lack of persistence when struggling with problems. Math anxiety is specifically negatively related to math skills (objectively and self-assessed) and to math attitudes. Contrarily it is not correlated (or sometimes positively correlated) with all these factors with regard to humanities.

The AMAS correlations with temperamental traits revealed an interesting pattern of results. Temperament as an elementary characteristic should be considered as primary to math anxiety and some attempts at explaining math anxiety may be based on temperamental traits. Math anxiety did not correlate with *Sensory Sensitivity* or *Activity*. A high positive correlation with *Emotional Reactivity* may be interpreted as an indication that math anxiety may be a form of an exaggerated emotional response toward math problems. On the other hand, a moderately positive correlation with *Perseverance* may suggest that math anxiety is increased by mentally elaborating too long about unsuccessful attempts to deal with the problem. A moderately negative correlation with *Endurance* and with *Briskness* may indicate that math anxiety is low in participants whose behavior can be described as highly energetic and persistent.

Interestingly, correlations with state and trait anxiety were moderate. This indicates that math anxiety cannot be accounted for by anxiety in general. Moreover, as predicted, correlations of math anxiety with state anxiety were numerically smaller than those with trait anxiety. Nevertheless, this difference in correlations did not reach significance ($p = 0.150$).

In the subsequent step we tested whether correlations between AMAS, MAAA, and Anxiety measures differ between the math and the non-math group. Surprisingly, virtually all correlations of AMAS scores and MAAA were significantly different from zero only in the non-math group. In the math group correlations with math-related items were smaller than 0.20 and in the large majority of cases not significantly different from zero. Only correlations with state and trait anxiety were significantly larger than zero. This effect was not caused by reduced variance e.g., because of floor or ceiling effects.

To further explore gender differences in AMAS scores we tested its correlations with external measures for female and male participants separately. As regards MAAA, correlations were stronger for female participants. In male participants correlations of *Learning* scale were null and non-significant. For *total* score and *Testing* scale correlations were smaller but significant. Reverse pattern of correlations was observed in case of state and trait anxiety measures. Its relation to AMAS scores were more pronounced in male participants.

In order to further explore relations between math anxiety, trait anxiety, and math skills (both grades and self-assessed skills) we performed path analyses. The first path analysis comprised relations between AMAS, trait anxiety and school grades. The path model together with standardized coefficients is presented in **Figure 3A**. The model reached satisfactory fit (RMSEA = 0.027) only when the path between trait anxiety and grades was set to 0. All depicted coefficients were significantly different from zero.

Assuming a possible relation between Math anxiety, trait anxiety and self-assessed math skill, the fit of the path model was worse, but still acceptable (RMSEA = 0.094), only when the relation between trait anxiety and math skill was fixed at 0. The path model together with the standardized estimates is presented in **Figure 3B**. All estimates were significantly different from zero. Henceforth, we can conclude that there is a specific relation between math anxiety and math performance, which cannot be accounted for by general anxiety.

Similarities and Differences between Results of AMAS between American, Italian, Iranian, and Polish Samples

In the last step of the analysis we examined whether the results obtained in our study resembled those reported in a study by Hopko et al. (2003) as well as Iranian (Vahedi and Farrokhi, 2011) and Italian (Primi et al., 2014) AMAS adaptations. The respective data are presented in **Table 3**.

As far as descriptive statistics are concerned, the results in all countries are very similar. Unfortunately, psychometric properties and statistics were not provided in all studies. In

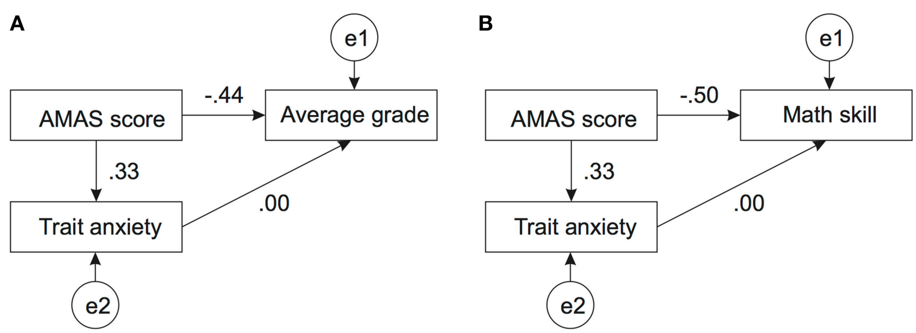

FIGURE 3 | Path model of the relation between trait anxiety, AMAS score, and math ability. Panel **(A)** depicts the relation between these two variables and the average math grade. Panel **(B)** depicts the analogous relation with self-assessed math skill. Both models reached satisfactory fit only when the relation between trait anxiety and the math ability measure was set to zero. All other coefficients were significantly different from zero. Variables labeled with e1, e2 etc…denote the respective error terms.

TABLE 3 | Comparison of the AMAS questionnaire results between the Polish (presented here), US-American (Hopko et al., 2003), Italian (Primi et al., 2014), and Iranian (Vahedi and Farrokhi, 2011) samples.

Measure	Polish sample	American: development sample	American: replication sample	Italian sample (college students)	Iranian sample
Mean Score (SD)	21.9 (6.6)	21.9 (7.0)	23.2 (5.8)	21.6 (6.3)	18.4 (6.8)[#]
Mean Score–Female participants (SD)	22.6 (6.6)	21.9 (6.9)	23.8 (5.7)	22.1 (6.0)	n.a.
Mean Score–Male participants (SD)	18.8 (6.7)	19.5 (6.9)	21.5 (5.7)	20.8 (6.6)	n.a.
Correlation between subscales[+]	0.49 (0.44–0.54)	0.62 (0.53–0.70)	n.a.	n.a.	0.50 (0.41–0.58)
Correlation *Learning*-total	0.85 (0.83–0.87)	0.88 (0.84–0.91)	n.a.	n.a.	0.85 (0.81–0.88)
Correlation *Testing*-total	0.88 (0.86–0.89)	0.91 (0.88–0.93)	n.a.	n.a	0.88 (0.85–0.90)
Cronbach Alpha–total	0.85 (0.83–0.86)	0.90 (0.88–0.92)	0.83(0.79–86)	0.85 (0.82–0.88)	0.82 (0.79–0.85)
Cronbach Alpha–*Learning*	0.78 (0.76–0.80)	0.85 (0.81–0.88)	0.74 (0.68–0.79)	0.80 (0.76–0.84)	0.75 (0.70–0.79)
Cronbach Alpha–*Testing*	0.84 (0.82–0.86)	0.88 (0.85–0.90)	0.81 (0.77–0.85)	0.83 (0.80–0.86)	0.79 (0.75–0.83)
Test-retest reliability total*	0.71 (0.67–0.74)	0.85 (0.81–0.88)	n.a.	n.a.	n.a.
Test-retest reliability *Learning**	0.59 (0.45–0.70)	0.78 (0.72–0.83)	n.a.	n.a.	n.a.
Test-retest reliability *Testing**	0.71 (0.60–0.79)	0.83 (0.78–0.89)	n.a.	n.a.	n.a.
Correlation AMAS and math grades	−0.44 (−0.49 to −0.38)	−0.52 (−0.61 to −0.41)	−0.34 (−0.45 to −0.22)	n.a.	n.a.

Several characteristics are similar. For further details please refer to the main text.

[#]*Inspection of the results from the Iranian study suggests that responses were coded from 0 to 4 instead of 1–5, therefore the average score reported here was obtained by adding nine to the average score reported in the original paper (see Table 2 there).*

For the Polish sample the test-retest delay was 4 months whereas for the US-American sample it was 2 weeks.

[+]*Numbers in parentheses after correlation/reliability estimate indicate 95%-confidence intervals.*

general, all other correlations are rather similar across the different language versions.

Correlations between the AMAS score and state and trait anxiety in the Polish and American sample were similar. Nevertheless, in case of the Polish sample, the correlation with trait anxiety was higher. Interestingly, the observed correlation between math anxiety and math achievement (self-reported, based on typical school grades) was stronger than the estimated population correlation between math anxiety and math achievement reported in a metaanalysis by Ma (1999). This may be due to differences in the measurement of math skills. Because such high correlations between math achievement and math anxiety in Poland were already found in the PISA study (see Lee, 2009), the current study points to culture-specific variations of validity of the AMAS.

DISCUSSION

Overview

Usefulness of the Polish version of the AMAS questionnaire was studied in a large sample of Polish adults. We observed few differences between cultures, but confirmed previously reported gender differences. Good psychometric properties (both validity and reliability) of the Polish version suggest the usefulness of the AMAS in another cultural and linguistic context that is somewhat different from those that were already tested, namely in an Eastern Europe culture.

AMAS Reliability

The AMAS is characterized by very good reliability properties as assessed by both Cronbach alpha as well as test-retest correlation. When the ordinal alpha coefficient, considered to be more suitable for the Likert scale response format (see Zumbo et al., 2007), was computed, the reliability estimates were even numerically higher. In our study, the 4-months period between initial testing and retest was quite long compared to typical test-retest reliability study designs, which usually encompass only a few weeks. Nevertheless, satisfactory test-retest estimates indicate that math anxiety is substantially stable over time. When interpreting the values, one must keep in mind that the retest sample was very homogeneous, comprising only psychology students. Therefore, reliability might be even higher for the general population.

AMAS Validity

Construct Validity

The factor structure obtained in the Polish sample supports a two-factor solution, one factor referring to math learning anxiety and the other to math testing anxiety. Based on our analysis, the item concerning being given difficult math homework should not be included in the *Learning* scale in our Polish sample. Factor loadings for this item were very similar for both factors. Double loadings are different from the original sample, but in our view not inconsistent with item content, because it refers both to learning and being exposed to evaluation afterwards. Normally, items with double loadings are excluded. However, this item is characterized by a strong item-total correlation and therefore, it would not be recommended to exclude it from the scale.

Convergent and Discriminant Validity–General Measures

The results of the convergent and discriminant validity analyses also revealed satisfactory results. As expected, the AMAS scores correlated moderately with state and trait anxiety, a trait measure for *Negative Emotionality,* a trait measure of *Perseverance,* and trait measure for *Endurance*. Highly math anxious individuals are somewhat more state- and trait-anxious in general, are more likely to respond with negative emotions in a wide range of situations, and have lower general endurance. The latter correlation is in line with the observation of local avoidance observed in highly math anxious individuals. When facing a math problem, these individuals tend to terminate the anxiety-evoking situation by impulsively providing the answer and not considering its accuracy (Ashcraft and Ridley, 2005). The correlations with other temperament trait measures were null or did not significantly deviate from zero, which may be taken as evidence for discriminant validity of the AMAS. Henceforth, we conclude that the AMAS is related to some general psychological characteristics. Nevertheless, the generally moderate correlations in a large sample suggest that math anxiety is a unique trait that cannot be reduced to or fully explained by those general traits discussed above. All these correlations hold irrespective of whether participants study math related or math unrelated subjects.

Convergent and Discriminant Validity–Math Related Measures

Indications for both, convergent and discriminant validity of the AMAS, were observed. The AMAS correlated negatively with self-assessed math skill, but the correlation between the AMAS score and self-assessed math skill in general was significantly larger than the correlation with self-assessed geometry skill. This is in line with results obtained in children by Vukovic et al. (2013), suggesting that math anxiety is more related to mathematical operations using abstract symbolic material.

The AMAS score also correlated with self-reported math grades at all levels of education. Furthermore, consistent with previous US-American studies, the correlation between self-assessed math skills was more pronounced than the correlation between math anxiety and (self-reported) school grades (Ashcraft and Ridley, 2005).

However, the relationship observed in our study is considerably stronger than the average correlation between math anxiety and math achievement (see: Ma, 1999). One must also keep in mind that we used self-reported math grades instead of official school documentation. However, it was shown that these measures are valid in US-American participants (as regards SAT score; see Nosek et al., 2002). What is more, the results of the PISA 2003 study suggest that in Poland the relationship between math anxiety and math achievement is above average (Lee, 2009). This literature suggests that the stronger relationship between math anxiety and math achievement in Poland may be real and not an artifact of the self-assessment question. Nevertheless, to be sure, this has to be examined in future studies.

Highly math anxious participants also reported getting discouraged more easily when facing difficult math problems, but not when writing an essay. This kind of behavior resembles the mechanism of local avoidance already described above. Highly math anxious participants also reported using more non-allowed aids than low anxious participants when solving math problems, but not when solving problems in humanities. Furthermore, highly anxious individuals also reported liking math less than low anxious individuals. This was more pronounced than the relationship between the AMAS score and liking science.

In sum, highly math anxious individuals report worse math performance and more specific negative attitudes toward math. However, this correlation pattern was present only in individuals from non-math group (i.e., those who study math unrelated subjects). In the math group we did not observe correlations between math related measures and math anxiety. This result deserves more attention in future studies.

Comparison of Four Language Versions of AMAS

In general, both average scores as well as important psychometrical properties of the AMAS were very similar for the US-American, Italian, Iranian and the Polish versions. Results of Polish version fall between results from other versions as regards average scores, correlations and reliability estimates. The only substantial difference was a lower test-retest reliability estimate of the *Learning* scale in Polish than in the US American sample (which is the only for which such reliability estimates are available). This is not necessarily due to a cross-cultural difference, because the Polish retest sample was very homogeneous and the test-retest interval was much longer—therefore lower reliability scores are to be expected. Furthermore, in the US American sample the subscales were more strongly correlated than in Polish sample, unfortunately such estimates were not provided in Italian and Iranian studies.

Gender Differences in Math Anxiety

The factor structure of AMAS was very similar for male and female participants (see note in Data Sheet 1). In our study we found a significant mean difference in math anxiety between male and female participants. This is in line with several studies conducted up to date. The estimated effect size can be considered middle sized ($d = 0.61$). This effect is stronger than the estimate provided by Hembree (1990) in his meta-analysis ($d = 0.31$). Interestingly, effect size of gender difference for all OECD countries PISA 2012 (OECD, 2013) study is almost the same ($d = 0.30$). As PISA study shows, this gender difference in Polish adolescents is very small ($d = 0.11$). Such discrepancy in estimated effect size of the gender difference may originate from the fact that participants of PISA study were adolescents (15-year-olds) whereas we tested students. The other reason may be that different instruments were used to measure math anxiety.

Interestingly, the observed gender difference was largely driven by *Testing* scale. However, it requires further investigation whether larger effect size in case of *Testing* scale originates from the fact that strong floor effect was observed in case of *Learning* scale. The other explanation could be that *Testing* scale may be more strongly related with test anxiety. It was shown that, contrarily to male, female individuals perceive testing situation as threat rather than challenge (Zeidner, 1998). Gender differences in test anxiety are most pronounced in its emotional aspect, and this pattern of results, together with higher test anxiety levels in female individuals is present in numerous and varied cultural and linguistic contexts (Zeidner, 1998). Our results thus suggest that gender differences in math anxiety may be modulated by test anxiety. This aspect deserves attention in further research. Interestingly, correlations between AMAS scores and math related measures were more pronounced in female participants whereas in case of state and trait anxiety this pattern was reversed. This effect deserves further attention in future studies. Furthermore, the observed gender difference may be partly driven by differences depending on the field of study, because we observed few significant correlations with math-related measures in participants with higher math expertise. The bigger gender difference in math anxiety observed in our study may be caused by the fact that the group of education students, which was very high in math anxiety—in line with American studies (see: Hembree, 1990)—was mostly comprised of female participants.

Explanations of such gender differences in math anxiety mostly refer to socio-cultural factors (Devine et al., 2012). Namely, male individuals are discouraged from expressing their anxiety. On the other hand, they are also expected to perform better in math.

Limitations of the Presented Study

One must keep in mind that our study is mostly based on self-reports. At first glance, this is self-explanatory when considering the nature of the constructs investigated. However, we argue that in light of the detailed results and the available literature, this does not undermine our conclusions in general, because for instance, the validity of self-reported math grades has previously been shown (Nosek et al., 2002).

Nevertheless, we have to admit that some of our results must be taken with some caution. First, participants provided their typical grades in math at several stages of their regular education.

Therefore, their reported grades had been given several years ago, possibly biasing the grades reported. One may also argue that it would be better to ask about scores in standardized math achievement tests. However, we believe that here, because of specificity of Polish educational system such questions would not be valid. First of all, standardized achievement tests are administered three times: after elementary school, after secondary school and after high school. Nevertheless, first two exams do not comprise math as a separate subject but it is a part of "science" module. Furthermore, in the exam after high school math was not compulsory for several years, so many of our participants could not have taken it. Second, the exam scores are used mostly for the purpose of next educational level applications and people usually do not remember how many points they scored. Furthermore, the responses observed for items from the MAAA scale were given at the same time, and the content of the items was similar. It is easily possible that the correlation between responses to several items may to some extent have been driven by this similarity. Moreover, attitudes toward humanities may be rated by contrasting them to responses to items referring to math and science. Future studies should address these issues, for instance by constructing more complex and psychometrically validated scales of the respective attitudes. This is especially the case for the MAAA scale, because its items were constructed in such a way that responses to each item were considered as separate (each item referring to one aspect). No calculation of composite scores was possible (apart from the average math grade obtained by averaging math grades from all three stages of math education). As a consequence it was impossible to conduct a psychometric evaluation of this scale.

Finally, objective measures of math ability and achievement should be utilized. This is of particular importance since the relationship between math anxiety and performance differs considerably when different measures of achievement are involved, as reported in the meta-analysis by Ma (1999). The relationship is stronger when teacher assessments as well as research methods are used in order to measure performance. The magnitude of this relationship is smaller when standardized achievement tests are utilized (Ma, 1999). All these factors may have increased some correlations with other constructs.

However, there is also one limitation that may have led to a decrease in correlations or even may make the overall picture of math anxiety too simplified. Our study sample was only comprised of university students and was homogeneous as regards age and educational level (as expressed by total number of years of education). However, it has shown considerable differences in correlations of math anxiety depending on field of study. Henceforth, further research should test more heterogeneous samples (elderly people, adolescents, individuals who have no educational experiences at universities). This is of particular importance in order to extrapolate our conclusions to the general population.

In sum, the general pattern of correlations is consistent with the literature and the assessment of traits and performance used here has generally shown to be valid in previous studies. Therefore, we are confident that the general pattern of results, which is largely consistent with the pattern of other samples, is valid. However, it is possible that the level of the observed correlations and effect sizes will differ for other sample characteristics, assessment tools or assessment procedures. All these questions deserve further investigation.

OVERALL CONCLUSIONS

Based on the results of our study, we conclude that the AMAS scale in the present form can be used for the Polish population. More interestingly, the presented study provides further support for the claim that the math anxiety construct might be generalized across many cultures. Gender differences were confirmed in the present study; they were even a bit larger than reported so far. Keeping in mind the importance of math education, extensive research should be conducted in countries from several continents in order to develop adequate tools to measure math anxiety or to examine whether assessment tools developed in one country can be used in another. In case of the AMAS, our data suggests that this is the case.

AUTHOR CONTRIBUTIONS

KC and MS designed the study, collected the data and prepared the data for analysis. KC, HCN, and KW analyzed the data. KC, MS, HCN, and KW wrote the manuscript and accepted its final version.

ACKNOWLEDGMENTS

Hans-Christoph Nuerk was supported by the LEAD Graduate School and by the ScienceCampus Tuebingen (TP.8.4).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2015.01833

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 17 February 2016
doi: 10.3389/fpsyg.2016.00091

Components of Mathematics Anxiety: Factor Modeling of the MARS30-Brief

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Mathematics anxiety involves feelings of tension, discomfort, high arousal, and physiological reactivity interfering with number manipulation and mathematical problem solving. Several factor analytic models indicate that mathematics anxiety is rather a multidimensional than unique construct. However, the factor structure of mathematics anxiety has not been fully clarified by now. This issue shall be addressed in the current study. The Mathematics Anxiety Rating Scale (MARS) is a reliable measure of mathematics anxiety (Richardson and Suinn, 1972), for which several reduced forms have been developed. Most recently, a shortened version of the MARS (MARS30-brief) with comparable reliability was published. Different studies suggest that mathematics anxiety involves up to seven different factors. Here we examined the factor structure of the MARS30-brief by means of confirmatory factor analysis. The best model fit was obtained by a six-factor model, dismembering the known two general factors "Mathematical Test Anxiety" (MTA) and "Numerical Anxiety" (NA) in three factors each. However, a more parsimonious 5-factor model with two sub-factors for MTA and three for NA fitted the data comparably well. Factors were differentially susceptible to sex differences and differences between majors. Measurement invariance for sex was established.

Keywords: mathematics anxiety, confirmatory factor analysis, Mathematics Anxiety Rating Scale, sex differences, career choice

OPEN ACCESS

Edited by:
Carlo Tomasetto, University of Bologna, Italy

Reviewed by:
Prathiba Natesan, University North Texas, USA
Caterina Primi, University of Florence, Italy

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Specialty section:
This article was submitted to Cognition, a section of the journal Frontiers in Psychology

Received: *29 July 2015*
Accepted: *15 January 2016*
Published: *17 February 2016*

Citation:
Pletzer B, Wood G, Scherndl T, Kerschbaum HH and Nuerk H-C (2016) Components of Mathematics Anxiety: Factor Modeling of the MARS30-Brief. Front. Psychol. 7:91. doi: 10.3389/fpsyg.2016.00091

INTRODUCTION

High arousal and physiological reactivity in response to number manipulation are symptoms of mathematics anxiety (Richardson and Suinn, 1972; Dew et al., 1984; Faust, unpublished doctoral dissertation). They lead to avoidance of careers that require mathematical skills (Ashcraft and Faust, 1994; Ashcraft and Kirk, 2001; Hopko et al., 2001). Accordingly, women typically have higher values of mathematics anxiety than men (e.g., Devine et al., 2012) and mathematics anxiety differs across college majors (e.g., Preston, 1986, but see Hamza et al., 2011). However, mathematics anxiety may therefore contribute to impaired life functioning (e.g., Hopko et al., 2001).

Therefore quick and efficient identification of mathematics anxious persons by standardized instruments is important for intervention (see Richardson and Suinn, 1973 for an intervention study). For application in adults Richardson and Suinn (1972) constructed a measure of anxiety related to mathematics originally consisting of 98 items – the Mathematics Anxiety Rating Scale (MARS), which has been validated by several studies (Richardson and Suinn, 1972, 1973; Suinn et al., 1972; Brush, 1978; Morris et al., 1978). Since then, several studies developed abbreviated forms in order to reduce administration time or eliminate contaminated items that did not fit data (69 and 25 items by Alexander and Martray, 1989; 10 items by Ferguson, 1986; 34 items by Fujii, 1994; 12 items by Hopko, 2003; 67 items by Levitt and Hutton, 1984; 24 items by Plake and Parker, 1982; 94 items by Rounds and Hendel, 1980; see also **Table 1**). Summarizing results of Rounds and Hendel (1980), Alexander and Cobb (1987) and Alexander and Martray (1989), the authors of the original instrument themselves constructed a shortened scale consisting of 30 items, called the MARS30-brief (Suinn and Winston, 2003). They report a Cronbach's alpha of 0.96 and test–retest reliabilty of 0.90 for this instrument and consider it to be comparable to the original 98 item scale.

Several studies tried to disclose the factor structure of mathematics anxiety by applying factor analyses to different versions of the MARS. **Table 1** gives an overview of the factor structures obtained with different extraction methods, different samples, and test versions. Generally, a global 2-factor-structure is widely accepted (Rounds and Hendel, 1980; Alexander and Cobb, 1987). Different authors distinguish between two aspects of mathematics anxiety: "Mathematics Test Anxiety" (MTA) describing anxiety associated with learning for mathematics tests and being evaluated in mathematics, and "Numerical Anxiety" (NA) describing anxiety associated with the manipulation of numbers, basic arithmetic skills, and monetary decisions in everyday situations (see Rounds and Hendel, 1980; Alexander and Cobb, 1987).

Since mathematics test-related items evoke more anxiety than task- or course-related items (Alexander and Martray, 1989) some authors consider MTA to be the more important factor of mathematics anxiety and NA to play only a secondary role (Plake and Parker, 1982; Alexander and Martray, 1989). Therefore, Plake and Parker (1982) developed the MARS-R, which consists only of items concerning the MTA-factor. However, these authors still tried to base their measure on a multilevel model of mathematics anxiety and take into account that it is related to general state-, trait-, and test-anxiety. These authors described 2 subscales of the MARS-R or MTA: "Learning Mathematics Anxiety" (LMA), concerning learning for mathematics tests or homework, and "Mathematics Evaluation Anxiety" (EA), concerning mathematics tests and exams. This structure has been validated and replicated through confirmatory factor analysis by Hopko (2003). Interestingly, Alexander and Cobb (1987) assign a subset of items categorized as "Course Anxiety" to the MTA-factor, which are considered to be part of the NA scale by other authors (see **Table 1**). In summary, most studies report a one or two-factor structure of the MTA scale.

Regarding the factor structure of the global dimension NA, studies reveal a more fine-grained factor structure. The NA-factor is subdivided into "Everyday Numerical Anxiety" (ENA, Bessant, 1995), "Performance Anxiety" (PA, Bessant, 1995), "Social Responsibility Anxiety" (SRA, Resnick et al., 1982), "Observation Anxiety" (OA, Bessant, 1995), and "Problem Solving Anxiety"

TABLE 1 | Factors of Mathematics Anxiety: overview of a variety of factor analytic studies on different versions of the MARS.

	Extraction method	Sample (%) females	MARS version	MTA		NA				
				LMA	EA	CA/OA	SRA	ENA	PA	PSA/AA
Rounds and Hendel, 1980	PCA Varimax rotation	350 (100)	94 items → 86 items	42 items		44 items				
Brush, 1978	PCA Varimax rotation	189 (51) students	94 items	45 items		31 items				
Suinn and Winston, 2003	PCA Oblique rotation	124 (51) psychology students	MARS30-brief	? items		? items				
Ferguson, 1986	PCA Varimax rotation	365 (?) college students	Phobos 30 items	? items		? items				10 items
Alexander and Martray, 1989	PCA Varimax rotation	517 (?) college students	69 items → sMARS 25 items	15 items		5 items		5 items		
Resnick et al., 1982	PCA Varimax rotation	1045 (?) students	94 items → 30 items	19 Items			4 items	7 items		
Alexander and Cobb, 1987	PCA	197 (?) college students	MARS → 41 items	34 items			7 items			
Bessant, 1995	PCA ? Quartimax rotation	173 (59) psychology students	80 items canadian assimilation	52 items	? items	? items		? items	? items	? items
Jänen et al., 2006	PCA Orthogonal rotation CFA	666 (48) pupils	MARS-E (german)	5 items	5 items	4 items		6 items		
Plake and Parker, 1982	PCA Varimax rotation	170 (?) graduate students	MARS-R 24 items	16 items	8 items					
Hopko, 2003; Hopko et al., 2003	CFA	815 (51) students	MARS-R 24 items → AMAS12 items	8 Items	4 items					

PCA, Principal component analysis; CFA, confirmatory factor analysis; MTA, Mathematics Test Anxiety; LMA, Learning Mathematics Anxiety; EA, Evaluation Anxiety; NA, Numerical Anxiety; SRA, Social Responsibility Anxiety; PA, Performance Anxiety; AA, Abstraction Anxiety; OA, Passive Observation Anxiety; CA, Course Anxiety; ENA, Everyday Numerical Anxiety; PSA, Problem Solving Anxiety.

(PSA, Bessant, 1995), or "Abstraction Anxiety" (AA, Ferguson, 1986). ENA involves private calculations in everyday situations, while PA includes performance pressure induced by being told to solve mathematical problems. SRA concerns everyday life situations demanding social responsibility, e.g., memorizing figures for a driving license test. OA involves watching someone working on mathematical problems, with a calculator or on the blackboard. PSA/AA concerns abstract mathematical problem solving like equations or ratios. As can be depicted from **Table 1** a great variety of factor solutions has been obtained for the items pertaining to the NA scale.

In summary, the factor structure of mathematics anxiety remains unclear. Different reasons for this may be pointed out: In part this can be attributed to the large diversity of (i) extraction methods and (ii) item sets employed, and (iii) assignment of items to factors.

(i) First, a great variety of methods employed to investigate the covariance structure of the MARS can be observed (**Table 1**). While most authors have worked with exploratory methods for determining the number of factors necessary for accounting for a substantial proportion of variance (principal components analysis with different rotation methods, scree plot, fixation of the number of factors), only one study has so far used confirmatory factor analysis to investigate whether the MTA-factor consisted of one or two subfactors. On the one hand, exploratory methods imply dangers concerning overfactorization in the final item selection (Fabrigar et al., 1999). For instance, when the average item covariance is relatively low, the exploratory solution may reveal too many factors. On the other hand, relevant portions of the covariance structure of the original items set may be overseen when many items were eliminated, because they load on two or more separate factors simultaneously.

(ii) Secondly, the item selection in the different studies differed widely and was often not even explicitly reported. Some studies obtained their abbreviated versions not from the original 98-items scale, but from non-validated abbreviated item subsets. For instance, Rounds and Hendel (1980) ran a factor analysis over 94 out of the 98 original items, while Bessant (1995) used only 80 items and Alexander and Martray (1989) 69 items. Furthermore, Ferguson (1986) used 20 items that according to Rounds and Hendel (1980) loaded on one of the two factors MTA and NA, as well as 10 further items referring to abstract mathematical topics. The MARS-R of Plake and Parker (1982) consisted mainly of Items of the MTA-factor and, according to the authors, was designed for application in "*statistically related situations*" (Plake and Parker, 1982, p. 552). Problems with the lack of selection criteria may cumulate over studies when authors develop new reduced versions of the MARS from abbreviated item sets taken from the literature (Resnick et al., 1982; Hopko, 2003). As a result, the factor structure of abbreviated versions of the MARS may tap on very specific subset of the dimensions described in the literature (**Table 1**). To summarize, the widely varying item selections for different factor analyses may have led to very differing empirical and theoretical factor solution. In particular, some reduced version of the MARS may ignore important dimensions of mathematics anxiety and may be useful only for investigating specific aspects of this construct.

(iii)Third, the assignment of items to factors as described in the literature is very often incomplete. While, Plake and Parker (1982), Ferguson (1986), Alexander and Martray (1989), and Hopko (2003) reported exactly the assignment of all items surviving factor analysis to their respective factors as well as their loads in these factors, other authors have reported the assignment of items to factors only in an illustrative way. Therefore, it is possible that some items may have been assigned to different factors over different studies. Once more the unclear assignment of items to determined factors may lead to problems with the conceptual interpretation of the different dimensions of mathematics anxiety.

For these reasons further investigation on the factor structure of mathematics anxiety is still necessary. Specifically, it is relevant to determine (i) whether the traditional two-factor model by Rounds and Hendel (1980) is sufficient for describing the dimensionality of mathematics anxiety, (ii) whether these two factors as second-order factors can be dismembered into several smaller first-factors in a hierarchical CFA model and (iii) whether the second-order factors are necessary for describing the dimensionality of mathematics anxiety. In the present study we therefore examined and compared these three confirmatory factor analytic models. Especially, the MARS is probably still the most widely used mathematics anxiety questionnaire and the MARS30-brief is its present (abbreviated) version. While Richardson and Suinn (1972) report an internal consistency of 0.97 and a test–retest reliability of 0.85 for the MARS, Suinn and Winston (2003) report an internal consistency of 0.96 and test–retest reliability of 0.90 for the MARS-30 brief. According to the authors, validity data also support the comparability of the two measures. Thus, the MARS30-brief can be considered an economical equivalent of earlier versions of the MARS, which has been constructed under consideration of results from earlier studies, also accounting for their deficiencies in selection of samples and item sets. Therefore, disclosing its factor structure is of great empirical interest. To our knowledge, the factor structure of the current version of this diagnostic instrument has not been investigated with confirmatory factor analytic techniques yet. Therefore, in the present study the factor structure of the MARS30-brief was examined.

Establishing the factor structure of mathematics anxiety may help identifying, which aspects of the construct lead to the avoidance of careers requiring mathematical skills. When considering MTA and NA, it is of interest, whether the anxiety pertains to the performance of mathematics in itself, irrespective of the situation, or whether the anxiety is more strongly attributed to the test situation. The present study aims to evaluate, whether more sub-factors are necessary to gain an even closer picture of where and when the anxiety manifests for an individual. In particular it may be relevant, whether it already leads to the avoidance of learning math (LMA) or only to the avoidance of test situations (EA) or whether it leads to the avoidance of performing math in everyday life altogether (ENA) or only in situations of social responsibility (SRA).

Identifying, which aspects of math anxiety are most important for a person, is, however, of importance for successful intervention. Therefore, in the present study, after establishing the factor structure of the MARS30-brief, we will also assess individual differences in these sub-factors, particularly gender differences and differences between college majors. While gender differences and differences between college majors are commonly accepted for mathematics anxiety, only few studies have so far distinguished between different components of mathematics anxiety in these comparisons. This may in part be attributable to the fact that inconsistencies already arise, when taking only the two factors MTA and NA into account. According to Evans (2000) higher values in women were confirmed for both MTA and NA, whereas Baloğlu and Koçak (2006) report higher MTA values in women, but higher NA values in men using a revised version of the MARS. Furthermore, it has been suggested based on different relationships of MTA and NA to age and attitudes toward mathematics in men and women that the factor structure of the mathematics anxiety may differ between men and women (Wilder, 2012). This has, however, not been confirmed using confirmatory factor analytic models. Therefore, we will establish measurement invariance prior to our gender comparisons, while the comparisons between majors need to remain exploratory due to small sample sizes in some groups. However, to the best of our knowledge, it has not been previously investigated, whether gender differences and differences across college majors, concern all sub-factors of MTA and NA or whether some factors are more sensitive for gender- and major-differences than others.

MATERIALS AND METHODS

Participants

Participants were 491 students (330 women, 161 men, mean age: 21.78 years, SD = 4.05 years; range: 18–55 years) at the University of Salzburg. 162 of the participants (96 women, 66 men) were enrolled as psychology majors, 179 (124 women, 55 men) were enrolled as biology majors, 46 (26 women, 20 men) were enrolled as mathematics majors and 66 (55 women, 11 men) were enrolled as language majors. The remaining 38 participants were from other majors (e.g., education, history, geography) or did not provide any information about their major. The latter were not included in analyses comparing mathematics anxiety between majors.

Ethics Statement

Participants were informed about the aims of the study and gave a written consent authorizing data processing for research purposes. Participation in the present study was voluntary. To assure anonymity in data processing, a numerical code was assigned to each participant. All methods conform to the Code of Ethics of the World Medical Association (Declaration of Helsinki).

The institutional guidelines of the University of Salzburg (Statutes of the University of Salzburg – see http://www.uni-salzburg.at/fileadmin/multimedia/Senat/documents/Satzung.pdf) state in §163 (1) that ethical approval is necessary for research on human subjects if it affects the physical or psychological integrity, the right for privacy or other important rights or interests of the subjects or their dependents. In §163, (2) it is stated that it is the responsibility of the PI to decide, whether (1) applies to a study or not. Therefore we did not seek ethical approval for this study. Since it was non-invasive and performed on healthy adult volunteers who gave their informed consent to participate, (1) did not apply.

Measure

The MARS30-brief was developed by Suinn and Winston (2003) and is a 30-item instrument for individual or group-administration. Items represent mathematics-related situations that may cause anxiety in the respondent. The translation into German was conducted by the first author and corrected by her supervisors for administration in German-speaking participants (see **Table 2** for item examples). Participants reported their level of anxiety associated with a particular item by checking the corresponding token in a scale from "not at all" (0), "a little" (1), "a fair amount" (2), "much" (3) to "very much" (4). Therefore, scores in the individual items ranged from 0 to 4. The MARS30-brief was administered in an auditorium of the University of Salzburg to all participants at once. Measure instructions were read aloud by an experimenter; the same instructions were also printed on the first page of the MARS30-brief's booklet. Instructing and administering the MARS30-brief took a total time of approximately 10 min. One and only one answer for each item was allowed. All participants conformed to these instructions – there were no missing data.

Analyses

To determine the factor structure of the MARS30-brief, a series of confirmatory factor models was calculated. We started the confirmatory factor analysis by examining the fit obtained for a default model (Model 0) for comparison, including only one global factor for mathematics anxiety (MARS). The first test model (Model 1) included two global factors, named "Mathematical Test Anxiety" (MTA) and "Numerical Anxiety" (NA). The assignment of items to factors MTA and NA was based on that reported by Rounds and Hendel (1980): We assigned items 1-15, all mentioning a mathematics test or exam to MTA, and items 16-30, all mentioning performing mathematics in everyday life to NA (see **Figure 1**). In a second model (Model 2), the factors MTA and NA were defined as second order factors (Marsh and Hocevar, 1985). Moreover, the first order factors EA and LMA were assigned to the second order factor MTA while the first order factors ENA, SRA, and PA loaded on the second order factor NA (see **Figure 2**). The assignment of items to EA, LMA, ENA, SRA, and PA was done as described in the literature (see Introduction and **Table 1**). All items referring to taking a mathematics examination were assigned to EA, all items referring to learning for a mathematics examination to LMA. All items referring to performing mathematics in everyday life (calculating a budget, reading a receipt) were assigned to ENA, all items referring to performing mathematics in a socially responsible role were assigned to SRA and all items simply referring to performing mathematics without giving a context (adding or dividing numbers on a paper) were assigned to PA. Item examples for each factor are listed in **Table 2**. The full list of items can be found in Suinn and Winston (2003).

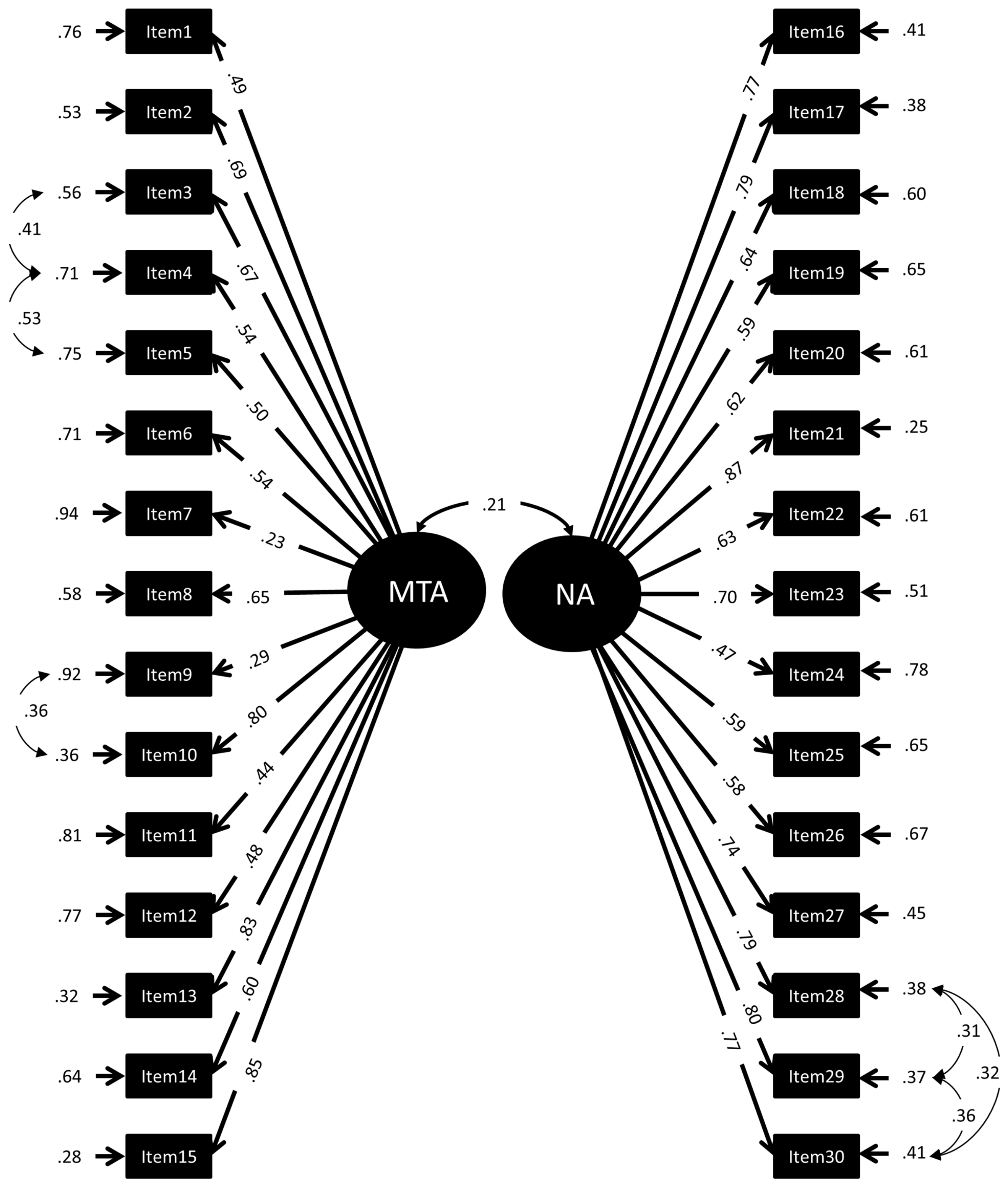

FIGURE 1 | Standardized Factor loadings, error variances, and correlations of a 2-factor-model of the MARS30-brief (Model 1). MTA, Mathematical Test Anxiety (items 1–15); NA, Numerical Anxiety (items 16–30).

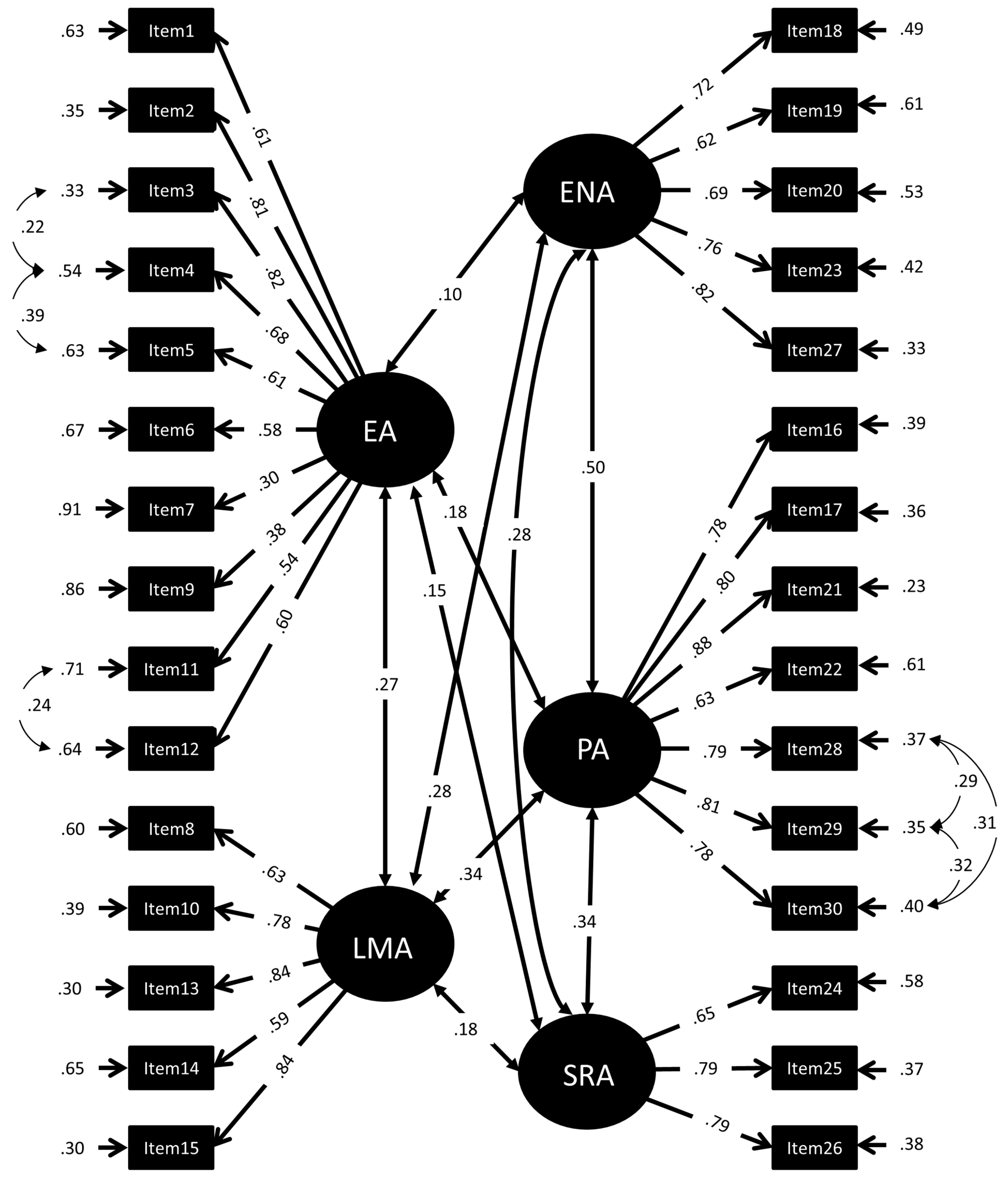

FIGURE 2 | Standardized Factor loadings, error variances, and correlations of a 5-factor-model of the MARS30-brief (Model 3). EA, Evaluation Anxiety; LMA, Learning Mathematics Anxiety; ENA, Everyday Numerical Anxiety; PA, Performance Anxiety; SRA, Social Responsibility Anxiety.

TABLE 2 | Item examples for each factor.

EA1	Item1	Taking an examination (final) in a mathematics course[a].
EA2	Item4	Thinking of an upcoming mathematics test on hour before.
LMA	Item10	Studying for a mathematics test.
ENA	Item20	Figuring out your monthly budget.
PA	Item21	Being given a set of numerical problems involving addition to solve on paper.
SRA	Item24	Being responsible for collecting dues for an organization and keeping track of the amount.

Note that Item 27 mentioned watching others work with a calculator, which would normally be assigned to OA. However, since this was the only item of this kind, it was assigned to ENA. The third model preserved only the first order factors of Model 2 but removed the second order factors (Model 3, see **Figure 3**).

These 3 Models were constructed following strictly the description of Factors in the literature (compare **Table 1**). However, we realized that Items 2–6, albeit mentioning a mathematics exam or test, did not refer to actually taking that exam, but to thinking about the exam. In order to test, whether thinking about an examination represented a different component of MTA than actually taking an examination, a fourth model was tested including six instead of five first order factors (Model 4, compare **Figure 4**). Model 4 included the same factors as Model 3, with the exception that EA was split into EA1, being EA proper (taking an examination) and EA2 (thinking about an examination).

The same correlations between error terms were allowed in each model for items 3–5 (*thinking about a mathematics examination a day/hour/minutes before it takes place*) and items 28–30 (*being supposed to perform divisions/additions/multiplications*), because their wording was very similar, in fact differed only in one word.

Since we observed gender differences on some factor scores, but not others, we additionally tested the comparability of each model between men and women. First, model fit was obtained for each group. Then measurement invariance was established. Since total sample size is larger than 300, strict criteria were used for measurement invariance analysis as recommended in Chen (2007). Measurement invariance for loadings and residuals was assumed, if the reduction in CFI did not exceed 0.01 and the reduction in RMSEA did not exceed 0.015.

Model estimation and comparison as well as tests for multivariate normality were carried out using the lavaan package for R. To evaluate Model fit we chose the Comparative Fit Index (CFI), since we want to compare the fit between different models, the Tucker–Luis index TLI as a relative fit index, which is not affected by sample size and does penalize adding additional parameters to the model and the Root Mean Square Error of approximation (RMSEA) as a badness of fit index that takes model complexity into account. Models were accepted, if CFI was >0.95. Further statistical analyses were carried out using the software SPSS version 20. In particular, sub-factor scores were compared to each other using Wilcoxon and Friedman-tests. The total MARS score and the sub-factor scores were compared non-parametrically between genders using Mann–Whitney U tests and between majors using Kruskal–Wallis and Mann–Whitney U tests. For Mann–Whitney U tests between majors, the significance level was Bonferonni-corrected to 0.008.

RESULTS

Normative Data

Participants reached an average total score of 36.83 (SD = 15.69, range: 1– 90). Ordinal alpha (based on the polychoric correlations) was 0.93. While this was lower than in the initial study of Suinn and Winston (2003) ($\alpha = 0.96$), it can be considered satisfactory. A significant Kolmogorov–Smirnov test suggested that the MARS30-brief total score deviated from a normal distribution in the present study ($Z = 1.46$, $p = 0.03$). Average responses and standard deviations as well as ordinal alpha with this item deleted are presented for each item in **Table 3**. As can be depicted from **Table 3**, deletion of items does not change the reliability of the scale.

Confirmatory Factor Analytic Models

The covariance structure presented by the 30 items of the MARS30-brief did not follow a multivariate normal distribution based on Mardias test for multivariate normality ($X^2 = 384.55$, $p < 0.001$) since neither multivariate skewness ($\beta_1 = 207.87$; $X^2 = 17010.56$, $p < 0.001$) nor multivariate kurtosis ($\beta_2 = 1347.63$; $Z = 98.01$, $p < 0.001$) were within an acceptable range. As indicated by significant Kolmogorov–Smirnov tests, each items deviated from a univariate normal distribution as well ($p < 0.001$). For this reason the CFA-model including all 30 items have been estimated with the unweighted least squares method of estimation (Bentler and Dudgeon, 1996; Schumacker and Lomax, 2004). Since ordinal data were obtained on a Likert scale, CFA-models were based on the polychoric correlation matrix and asymptotic covariance matrix.

In a first step, we evaluated the fit of the default model, with all items assigned to one factor MARS (Model 0). This model did not obtain a satisfactory model fit (compare **Table 4**), indicating that mathematics anxiety as assessed with the MARS30-brief is comprised of more than one factor.

In a second step different factor structures were tested and compared to the default model. To examine the two-factor structure reported by Rounds and Hendel (1980), we assigned items 1–15 all mentioning a mathematics test or exam to MTA and items 16–30 to NA (Model 1, **Figure 1**). The high X^2 value and borderline fit indices associated with Model 1 point out that this two-factor model cannot account for the covariance structure of data satisfactorily (**Table 4**). This suggests that the structure of mathematics anxiety is more fine-grained than a simple distinction of MTA and NA constructs. Importantly, however, the sum of scores for

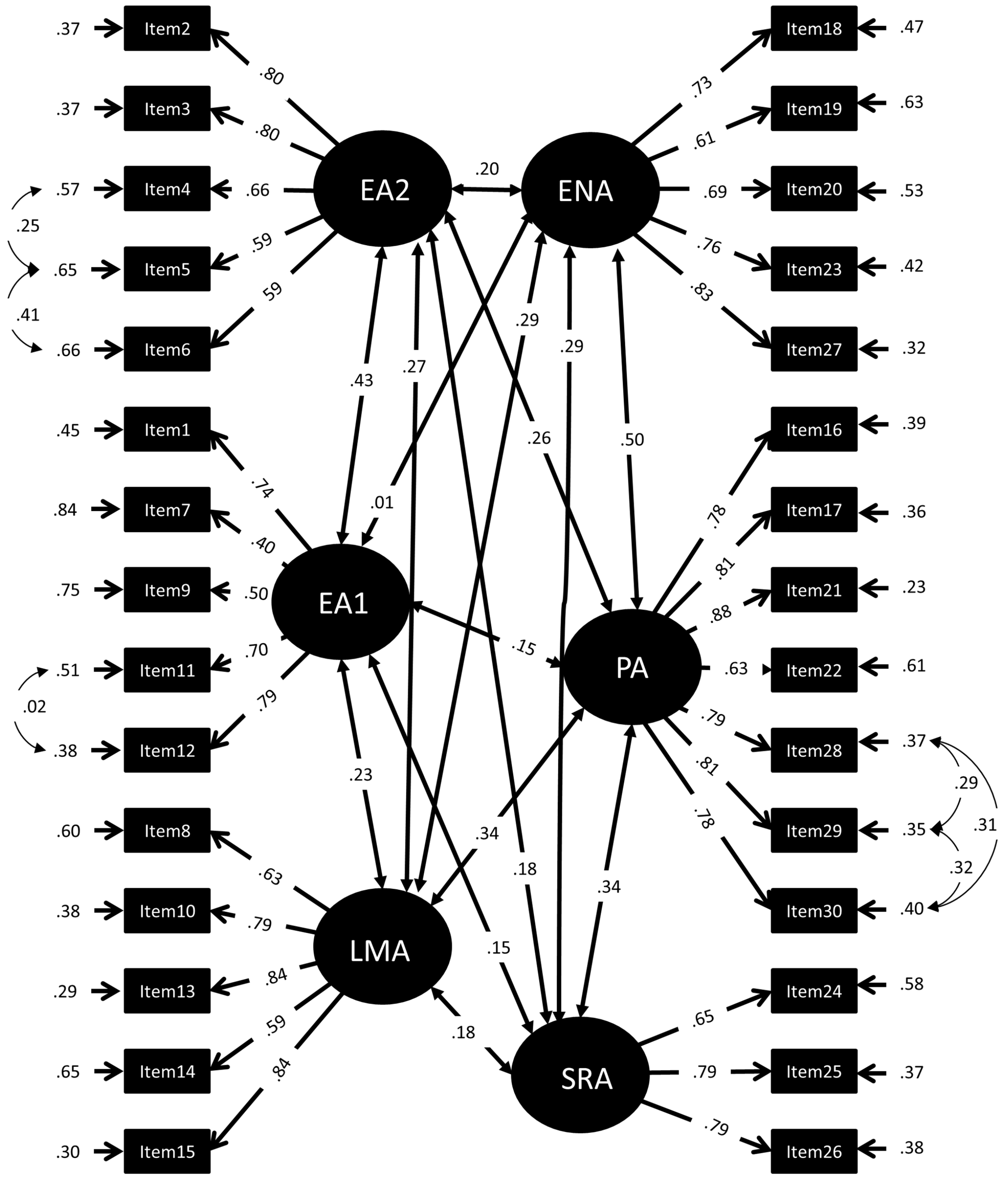

FIGURE 3 | Standardized Factor loadings, error variances, and correlations of a 6-factor-model of the MARS30-brief (Model 4). EA1, Evaluation Anxiety proper (taking mathematics tests); EA2, Evaluation Anxiety (thinking about mathematics tests); LMA, Learning Mathematics Anxiety; ENA, Everyday Numerical Anxiety; PA, Performance Anxiety; SRA, Social Responsibility Anxiety.

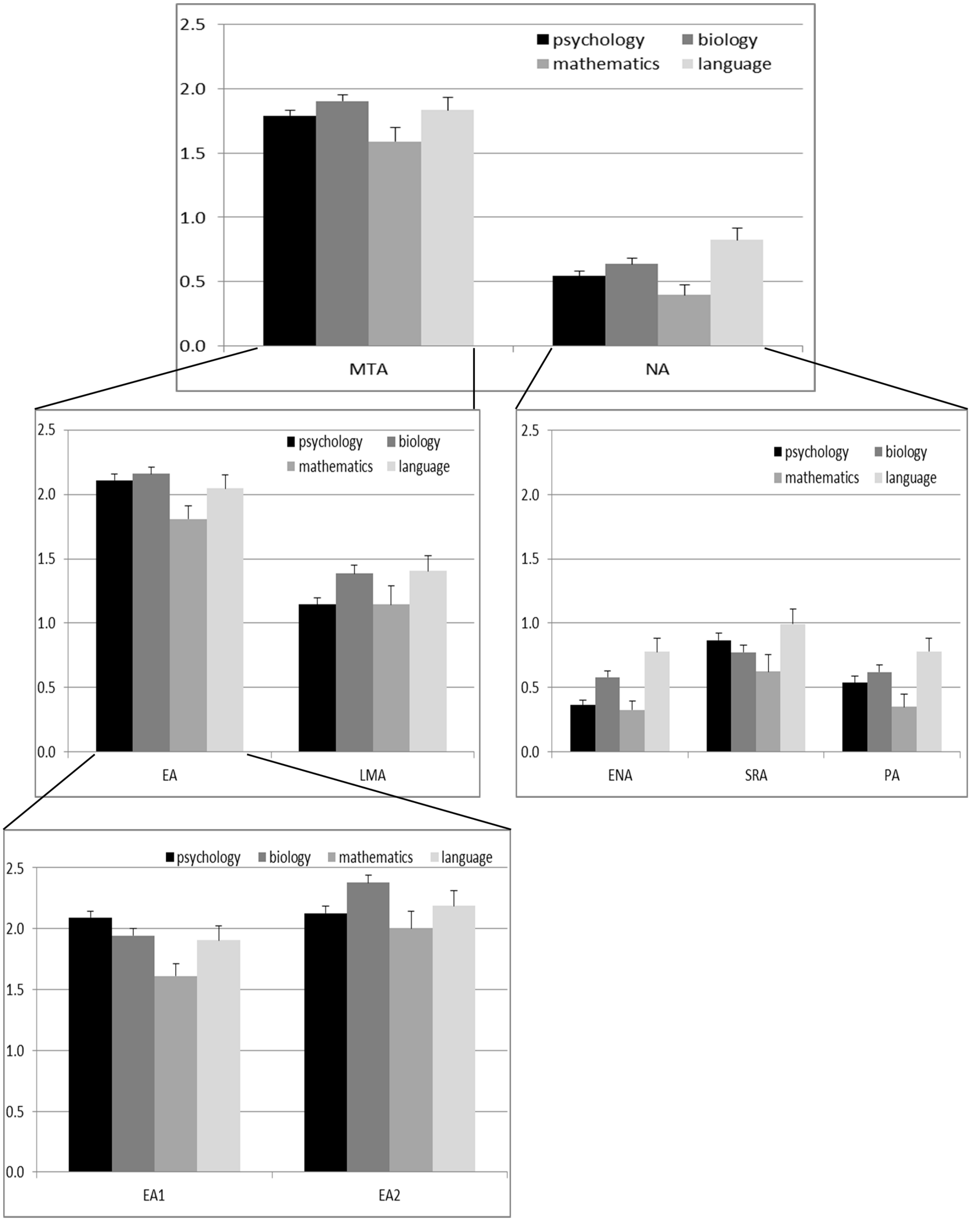

FIGURE 4 | Means ± SE for the different factors of mathematics anxiety split by major. MTA, Mathematical Test Anxiety (items 1–15); NA, Numerical Anxiety (items 16–30). EA, Evaluation Anxiety; LMA, Learning Mathematics Anxiety; ENA, Everyday Numerical Anxiety; PA, Performance Anxiety; SRA, Social Responsibility Anxiety; EA1, Evaluation Anxiety proper (taking mathematics tests); EA2, Evaluation Anxiety (thinking about mathematics tests).

TABLE 3 | Item statistics.

	Mean	*SD*	α if deleted	Skew	Kurtosis		*Mean*	*SD*	α if deleted	Skew	Kurtosis
Item 1	2.17	1.09	0.93	– 0.16	– 0.59	Item 16	0.53	0.98	0.93	1.95	3.09
Item 2	1.74	1.08	0.93	0.17	– 0.54	Item 17	0.37	0.89	0.93	2.60	6.07
Item 3	2.58	1.14	0.93	– 0.47	– 0.65	Item 18	0.44	0.99	0.93	2.37	4.77
Item 4	2.73	1.12	0.93	– 0.60	– 0.42	Item 19	0.42	0.77	0.93	2.05	4.14
Item 5	2.75	1.17	0.93	– 0.60	– 0.54	Item 20	0.75	1.07	0.93	1.44	1.28
Item 6	1.42	1.13	0.93	0.49	– 0.65	Item 21	0.47	0.83	0.93	1.88	3.10
Item 7	1.55	1.18	0.93	0.27	– 0.83	Item 22	0.98	1.07	0.93	0.96	0.14
Item 8	1.65	1.23	0.93	0.27	– 0.90	Item 23	0.73	0.94	0.93	1.26	1.13
Item 9	2.45	1.16	0.93	– 0.48	– 0.51	Item 24	1.02	1.01	0.93	0.83	0.09
Item 10	1.35	0.96	0.93	0.54	– 0.38	Item 25	0.76	0.93	0.93	1.14	0.72
Item 11	1.91	0.96	0.93	– 0.11	– 0.86	Item 26	0.75	0.90	0.93	1.10	0.67
Item 12	1.90	1.05	0.93	– 0.16	– 0.21	Item 27	0.23	0.64	0.93	3.27	11.54
Item 13	0.70	1.04	0.93	1.36	1.20	Item 28	0.75	0.96	0.93	1.21	0.81
Item 14	1.53	0.98	0.93	0.30	– 0.50	Item 29	0.53	0.84	0.93	1.71	2.73
Item 15	1.07	0.89	0.93	0.80	0.05	Item 30	0.58	0.90	0.93	1.60	2.08

TABLE 4 | X^2 and fit indices for the reported models.

	Model fit					Model comparison				
	Df	X^2	CFI	TLI	RMSEA	Model	ΔX^2	Δdf	*P*	
Model 0 (1 Factor)	399	4034.19	0.87	0.86	0.14					Reject
Model 1 (2 Factors)	398	2471.85	0.93	0.92	0.10	To Model 0	1562.30	1	<0.001	Reject
Model 2 (2-stages)	393	1702.98	0.95	0.95	0.08	Discarded due to negative error variances				
Model 3 (5 Factors)	389	1617.09	0.96	0.95	0.08	To Model 1	854.75	4	<0.001	Accept
Model 4 (6 Factors)	384	1373.70	0.97	0.96	0.07	To Model 3	243.39	5	<0.001	Accept

Model 1: two-factor model adapted from Rounds and Hendel (1980); Model 2: two stage model with two second order and six first order factors; Model 3: six-factor model with no second order factors. CFI, Comparative Fit Index; TLI, Tucker-Lewis Index; RMSEA, Root Mean Square Error of Approximation, for all models p < 0.05.

TABLE 5 | Factor pattern and structure coefficients for Models 3 (5 Factor) and 4 (6 Factor).

	Model 3 (5 Factor)		Model 4 (6 Factor)			Model 3 (5 Factor)		Model 4 (6 Factor)	
Item	**Factor**	**Coefficient**	**Factor**	**Coefficient**	**Item**	**Factor**	**Coefficient**	**Factor**	**Coefficient**
Item 2	EA	0.35	EA1	0.37	Item 18	ENA	0.49	ENA	0.47
Item 3	EA	0.32	EA1	0.37	Item 19	ENA	0.61	ENA	0.63
Item 4	EA	0.54	EA1	0.57	Item 20	ENA	0.53	ENA	0.53
Item 5	EA	0.63	EA1	0.65	Item 23	ENA	0.42	ENA	0.42
Item 6	EA	0.67	EA1	0.66	Item 27	ENA	0.33	ENA	0.32
Item 1	EA	0.63	EA	0.45	Item 16	PA	0.39	PA	0.39
Item 7	EA	0.91	EA	0.84	Item 17	PA	0.36	PA	0.35
Item 9	EA	0.86	EA	0.75	Item 21	PA	0.23	PA	0.23
Item 11	EA	0.71	EA	0.51	Item 22	PA	0.61	PA	0.61
Item 12	EA	0.63	EA	0.38	Item 28	PA	0.37	PA	0.37
Item 8	LMA	0.60	LMA	0.60	Item 29	PA	0.35	PA	0.35
Item 10	LMA	0.39	LMA	0.38	Item 30	PA	0.40	PA	0.40
Item 13	LMA	0.30	LMA	0.29	Item 24	SRA	0.58	SRA	0.58
Item 14	LMA	0.65	LMA	0.65	Item 25	SRA	0.37	SRA	0.37
Item 15	LMA	0.30	LMA	0.30	Item 26	SRA	0.38	SRA	0.37

EA, Evaluation Anxiety; EA1, Evaluation Anxiety proper (taking an examination); EA2, thinking about an examination; LMA, Learning Math Anxiety; ENA, Everyday Numerical Anxiety; PA, Performance Anxiety; SRA, Social Responsibility Anxiety.

TABLE 6 | Latent Factor correlations for Model 3 (5 Factors, below diagonal) and Model 4 (6 Factors, above diagonal).

		EA		LMA	ENA	PA	SRA
		EA1	EA2				
EA	EA1		0.43	0.23	0.01	0.15	0.15
	EA2			0.27	0.20	0.26	0.18
LMA		0.27			0.29	0.34	0.18
ENA		0.10		0.28		0.50	0.29
PA		0.18		0.34	0.50		0.34
SRA		0.15		0.18	0.28	0.34	

EA, Evaluation Anxiety; EA1, Evaluation Anxiety proper (taking an examination); EA2, thinking about an examination; LMA, Learning Math Anxiety; ENA, Everyday Numerical Anxiety; PA,Performance Anxiety; SRA, Social Responsibility Anxiety.

TABLE 7 | Measurement invariance between men and women for Model 3 (5 Factor).

	Model fit				Model comparison						
	Df	X^2	CFI	RMSEA	Model	ΔX^2	Δdf	ΔCFI	ΔRMSEA	*P*	
Configural	778	2042.60	0.96	0.08							Accept
Loadings	803	2197.60	0.95	0.08	To configural	154.94	25	<0.01	<0.015	<0.001	Accept
Intercepts/residuals	888	2401.60	0.95	0.08	To loadings	204.01	85	<0.01	<0.015	<0.001	Accept
Means	893	2894.30	0.93	0.10	To residuals	492.74	6	>0.01	> 0.015	<0.001	Reject

TABLE 8 | Measurement invariance between men and women for Model 4 (6 Factor).

	Model fit				Model comparison						
	Df	X^2	CFI	RMSEA	Model	Δ X2	Δ df	Δ CFI	Δ RMSEA	*P*	
Configural	768	1787.50	0.97	0.07							Accept
Loadings	792	1904.60	0.96	0.08	To configural	117.16	24	<0.01	<0.015	<0.001	Accept
Intercepts/residuals	876	2133.40	0.96	0.08	To loadings	228.74	84	<0.01	<0.015	<0.001	Accept
Means	882	2632.00	0.94	0.09	To residuals	498.67	6	> 0.01	= 0.013	<0.001	Reject

MTA (Items 1–15; 27.50 ± 9.85) were significantly higher than the sum or scores for NA (items 16–30; 9.33 ± 8.81; $Z = 18.75$; $p < 0.001$). Ordinal alphas of MTA and NA were both 0.89.

In Model 2 the two-factor structure was dismembered into a hierarchical CFA structure with the two original MTA and NA factors as second order factors. To second order factor MTA the first order factors EA and LMA were assigned and to the second order factor NA the first order factors ENA, PA, and SRA. This model resulted in negative error variances, suggesting a bad fit for the data and was therefore discarded. Therefore, Model 3 included only the five factors EA, LMA, ENA, PA, and SRA, but the second order factors MTA and NA were removed (**Figure 2**). The X^2 value associated with Model 3 was significantly lower than that of Models 1 and model fit was much better. This suggests that a non-hierarchical five-factor model describes the factor structure of the MARS30-brief better than the two-factor solution in Model 1. Ordinal alphas of the 5 factors in the CFA-model were 0.86, 0.86, 0.84, 0.89 and 0.96 for EA, LMA, ENA, SRA, and PA, respectively. Average scores for EA (2.11 ± 0.71) were significantly higher than for LMA (1.26 ± 0.81; $Z = 16.75$, $p < 0.001$). Furthermore, the scores on the sub-factors of NA did differ significantly from each other as indicated by a Friedman test ($X^2 = 99.57$, $p < 0.001$). As indicated by Wilcoxon comparisons (all $Z > 4.16$, all $p < 0.001$), ENA (0.52 ± 0.03) was significantly lower than PA (0.60 ± 0.04) and SRA (0.84 ± 0.04), while SRA was significantly higher than PA and ENA.

Furthermore we tested, whether model fit could be further improved, by dismembering the EA factor into EA1 (taking an examination) and EA2 (thinking about an examination), which has not been described in the literature before (**Figure 3**). Indeed, the model fit obtained by this model (Model 4) was best and the X^2 value was significantly lower than in Model 3. This suggests that other than described in the literature the MTA factor was comprised of more than two components, since taking an examination and thinking about a examination comprised different sub-factors of MTA. Ordinal alphas of EA1 and EA2 were 0.73 and 0.83, respectively. Average scores for EA1 (1.99 ± 0.78) were significantly higher than average scores for EA2 (2.25 ± 0.85; $Z = 5.85$, $p < 0.001$).

Model comparisons are also displayed in **Table 4** indicating that Model fit was significantly improved in each step. **Tables 5** and **6** provide the factor pattern, coefficients and factor correlations for Models 3 and 4.

Gender Differences

An analysis of measurement invariance was conducted on Models 3 and 4 to see whether the same factor structure can be obtained for men and women. First, Models 3 and 4 provided comparably good fit for both the male (Model 3: $X^2 = 726.10$, df = 389, CFI = 0.96, TLI = 0.96, RMSEA = 0.07; Model 4: $X^2 = 676.65$, df = 384, CFI = 0.97, TLI = 0.96, RMSEA = 0.07) and female subsample (Model 3: $X^2 = 1316.53$, df = 389, CFI = 0.95, TLI = 0.95, RMSEA = 0.09; Model 4: $X^2 = 1110.81$, df = 384, CFI = 0.96, TLI = 0.96, RMSEA = 0.07). Results for different types of measurement invariance are displayed in **Tables 7** and **8**. While each additional constraint significantly reduced the X^2 value of the model, model fit remained acceptable until the last step. Thus, mean factor scores can be compared between men and women.

As described in the literature, the MARS total score was significantly higher in women (38.48 ± 15.67) than in men (33.42 ± 15.22) ($Z = 3.18$, $p = 0.001$). Gender differences were only observed in the first 15 items (MTA; $Z = 4.40$, $p < 0.001$), but not in the second 15 items (NA; $Z = 0.33$, $p = 0.74$). Gender differences were furthermore confirmed for all sub-factors of MTA (LMA, EA, EA1, and EA2; all $Z > 2.48$, all $p < 0.05$), but only for the sub-factor PA of NA ($Z = 1.97$, $p < 0.05$), not for ENA and SRA (both $Z < 0.79$, both $p > 0.43$).

Differences Between Majors

Due to small sample sizes in some subgroups analyses of measurement invariance across majors could not be conducted. Therefore the following results are exploratory.

The MARS total score differed significantly between major subjects ($X^2 = 15.70$, $p = 0.001$). Mathematics majors had significantly lower values than biology and language majors (all $Z > 3.15$, all $p < 0.002$). Psychology majors had by trend higher values than mathematics majors ($Z = 2.32$, $p = 0.02$), but by trend lower values than biology or language majors (both $Z > 1.96$, both $p < 0.05$). Biology and German majors had comparable values ($Z = 0.55$, $p = 0.58$). Major subject had a significant impact on both MTA and NA. However, Mann–Whitney U tests indicated that while for MTA highest scores were obtained by biology majors (significantly higher than mathematics majors, $Z = 2.74$, $p = 0.002$), for NA highest scores were obtained by language majors (significantly higher than psychology and mathematics majors, $Z = 3.79$, $p < 0.001$; compare **Figure 4**). Significant differences between the majors were also observed for all sub-factors of MTA and NA (all $X^2 > 8.64$, all $p < 0.05$). Interestingly, for both EA and LMA the highest scores were obtained by biology majors. However, when split between EA1 and EA2, the highest scores for EA1 were obtained by psychology majors (significantly higher than mathematics majors, $Z = 4.07$, $p < 0.001$; not different from biology majors, $Z = 1.57$, $p = 0.12$), whereas only for EA2 the highest scores were obtained by biology majors (significantly higher than psychology majors, $Z = 3.06$, $p = 0.002$). For ENA, PA, and SRA, however, the highest scores were obtained by language majors.

DISCUSSION

As can be depicted from **Table 1** a great variety of factor solutions of mathematics anxiety exists. A global two-factor structure consisting of MTA and NA is widely accepted (Rounds and Hendel, 1980; Alexander and Cobb, 1987). However several studies report different sets of smaller factors. In the present study four factor analytic models were carried out in order to disclose the factor structure of mathematics anxiety, in particular the MARS30-brief. We wanted to determine (i) whether the traditional two-factor structure (i.e., MTA and NA as first order factors), first described by Rounds and Hendel (1980) is sufficient for describing the dimensionality of mathematics anxiety, (ii) whether MTA and NA can be dismembered into the first-order factors EA, LMA, ENA, PA, and SRA in a hierarchical CFA model and (iii) whether MTA and NA are necessary for describing the dimensionality of mathematics anxiety and (iv) whether EA could be further subdivided into EA1 (taking mathematics examinations) and EA2 (thinking about mathematics examinations). Furthermore, the present study aimed to evaluate, whether gender differences and differences across majors were comparable across all factors of mathematics anxiety and whether as a consequence the factor structure was comparable between men and women.

Our confirmatory factor models showed that (i) the two-factor structure was only borderline acceptable as description of the MARS30-brief in a single model, (ii) a hierarchical CFA factor structure having MTA and NA as second order factors described data equally well as the non-hierarchical five-factor model including EA, LMA, ENA, PA, and SRA. However, the best fit was obtained for a model including the six first order factors EA1, EA2, LMA, ENA, PA, and SRA. In the following these results will be discussed in more detail. Contrary to previous studies (Evans, 2000; Baloğlu and Koçak, 2006), gender differences with higher scores in women were observed only for MTA, not for NA, however, equally for all sub-factors of MTA (EA, EA1, EA2, and LMA). These differences were, however, not attributable to differences in the factor structure of the MARS between men and women, since measurement invariance for gender could be established. Differences across majors were observed for MTA, NA as well as all sub-factors except SRA. However, while the highest scores for MTA were obtained by biology majors, the highest score for NA were obtained by language majors. Furthermore, within the MTA, but not the NA, sub-factors differences were observed, with psychology majors showing the highest scores for EA1, while biology majors showed the highest scores for EA2 and LMA.

In Model 1 we examined the 2-factor structure consisting of MTA and NA which was reported by Rounds and Hendel (1980) for the original MARS and assumed by Suinn and Winston (2003) for the MARS30-brief. This assumption about the factor structure of the MARS30-brief was also supported by our descriptive and normative item characteristics. MTA and NA differ not only in their mean item scores, which are lower for factors of NA (compare also Alexander and Martray, 1989), but also in their distribution characteristics. While the 15 items of MTA do not deviate from a multivariate normal distribution, thereby replicating findings of Hopko (2003), items of NA violate the assumption of multivariate normality. Although these results may in part have been caused by the order of items, the strength of effects suggests that another reason is more plausible. One possible explanation is the increased relevance of test situations in comparison with everyday arithmetical problems in the population tested in this study, i.e., students. This does not mean that the average scores in NA may be necessarily low and present a non-normal distribution in every population. It could be suggested that the average scores in this part of the MARS30-brief scale should be higher in populations for whom the relevance of calculation in daily living situations is higher such as by bank workers or tradesmen. This assumption was in part confirmed by our data. On the one hand, gender differences were only apparent for MTA, but not NA. On the other hand different majors showed highest values for MTA (biology) and NA (language), indicating a higher relevance of mathematical tests for science majors, but higher relevance of everyday mathematical calculations for non-science majors. The fact that biology students show such a high degree of MTA also suggests that not all science majors can be grouped together in their evaluation of mathematics anxiety. This has, however, been done in previous comparisons of mathematics anxiety between college majors (Hamza et al., 2011). Such a grouping of all science majors may cause an over- or under-estimation of mathematics anxiety differences between majors and may cost some majors (e.g., biology majors) the necessary attention they require in dealing with their mathematics anxiety.

However, using confirmatory factor analytic techniques, we could not confirm the results obtained previously with principal components analysis and a fixed number of factors. Although taking into account error covariances, the X^2 value and fit indices of Model 1 were not satisfactory. Thus, our data clearly suggest that the two global factors MTA and NA are not sufficient for describing the factor structure of the MARS30-brief, but that its factor structure has more facets.

As an alternative hypothesis (ii) one could assume that the two dimensions MTA and NA perform better describing the covariance between the more specific first order factors. Therefore, in Model 2 the MTA – NA structure was dismembered into several smaller factors in a two stage two-factor model. This model, however, had to be discarded due to negative error variances, providing support for Models 3 and 4.

Model 3 and 4 differentiate better between different aspects of mathematics anxiety. Our factors EA and LMA replicate Hopko (2003), ENA, and PA have already been reported by Bessant (1995) and SRA by Resnick et al. (1982). Our Model 3 therefore includes all factors reported in the literature except OA and AA. However, OA was represented within the MARS30-brief by only 1 item (Item27), while the items of the construct AA were not originally contained in the MARS. It is to note that in contrast with findings of Bessant (1995), but replicating findings of Resnick et al. (1982), a strong association between factors ENA and PA was observed. Since Bessant (1995) forced factors ENA and PA as well as item residuals to be uncorrelated, it remains an open question, whether this association is generally high or only in our specific population.

However, contrary to the literature, the best model fit was obtained when further splitting EA into two factors capturing different aspects of EA, i.e., EA proper (taking and examination) as opposed to EA2 (just thinking about an examination). These two factors particularly seemed to induce different levels of anxiety across different majors with psychology majors showing particularly high values on EA1, but low values on all other aspects of mathematics anxiety. Furthermore, the correlation between EA1 and ENA was almost 0, whereas the correlation between EA2 and ENA was of moderate strength, suggesting different qualities of these two factors. We do note, however, that the results on differences between college majors need to be interpreted with care, since measurement invariance could not be established for these groups due to small sample sizes. Since Model fit of Model 3 is also acceptable and Model 3 is more parsimonious, Model 3 is probably the most practical model for research questions not evaluating differences between college majors.

In summary, the present findings on mathematics anxiety do not support the view that it can be reduced to MTA as has been suggested by Plake and Parker (1982) and Hopko (2003). Dew and Galassi (1983) and Dew et al. (1984) found that mathematics anxiety measures are more highly related to each other than to measures of test anxiety and therefore still reflect different aspects of personality. For a successful career it could rather be important to reduce SRA and PA to a reasonable and productive value. Through such an approach of differential diagnosis, intervention can target especially those constructs with high scores.

ACKNOWLEDGMENTS

We very much wish to acknowledge Richard Suinn for providing the MARS30-brief and all participants for their time and willingness to contribute to this study. Furthermore, we thank Ulrike Kipman for statistical advice.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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