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ORIGINAL ARTICLE

Math anxiety relates positively to metacognitive insight into mathematical decision making

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Abstract
The current study reports a pre-registered investigation into the interrelations between mathematics anxiety, metacognition and mathematical decision-making. Although this question has already received some attention in previous work, reliance on self-report measures of metacognition has hindered its interpretation. Here, a novel experimental mathematical decision-making task was used in which participants solved mathematical assignments of varying difficulty, and expressed their level of confidence in the accuracy of their decision both prospectively and retrospectively. Mathematics anxiety was measured using a standardized questionnaire. Both prospective and retrospective confidence judgments predicted unique variation in accuracy; however, the explanatory effect of prospective confidence disappeared after taking task difficulty into account. This suggests that prospective, but not retrospective, confidence is largely based on easily available cues indicative of performance. Results of a multiple regression analysis indicated that individual differences in mathematics anxiety were negatively related to the overall level of *confidence* (both prospectively and retrospectively), and positively related to metacognitive *efficiency* (only prospectively). Having insight in these interrelationships is important in the context of remediating mathematics anxiety, which might in turn be useful with regard to the worldwide need for more workers with degrees in science, technology, engineering, or mathematics (STEM).

Keywords Mathematics anxiety · Mathematical decision-making · Metacognition · Metacognitive efficiency · Meta-d'

Introduction

Mathematical performance is positively associated with life success, either expressed as economic and/or health outcomes (Dougherty, 2003; Gerardi et al., 2013; Parsons & Bynner, 2005; Valerie F. Reyna et al., 2009). As a consequence, nowadays, children and adolescents across the world are encouraged to subscribe in so-called STEM (Science, Technology, Engineering and Mathematics) education (e.g., in the US, see Olson & Riordan, 2012; in Europe, see Gago et al., 2004). Moreover, a lot of interest has been devoted to *cognitive* (e.g., Cragg, Keeble, Richardson, Roome, & Gilmore, 2017; Mayes, Calhoun, Bixler, & Zimmerman, 2009; Purpura, Schmitt, & Ganley, 2017; Träff, 2013) and *affective* (e.g., Ahmed Minnaert, Kuyper, & van der Werf, 2012; Henschel & Roick, 2017; Jansen, Louwerse, Straatemeier, Van der Ven, Klinkenberg, & Van der Maas, 2013; Pipere & Mieriņa, 2017) factors influencing mathematical performance. In this study, we focus on the interaction between the cognitive factor 'metacognition' and the affective factor 'mathematics anxiety', this way contributing to the new area of investigation that connects the metacognition literature with research on mathematical decision-making and mathematics anxiety (see also Morsanyi et al., 2019).

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Mathematics anxiety and mathematical performance

Mathematics anxiety was one of the first affective factors of which the impact on mathematical performance was systematically examined. 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…" (Richardson & Suinn, 1972, p. 551). Three meta-analyses have indeed shown a small to moderate negative correlation (– 0.27 and – 0.34) between mathematics anxiety and mathematical performance (Hembree, 1990; Ma, 1999; Namkung, Peng & Lin, 2019). The causal direction of that relation is, however, to date, not clear yet: does mathematics anxiety lead to avoidance of math-related activities and situations, resulting in less practice and consequently worse performance on math tests (Aschraft, 2002), or do repeated negative experiences with mathematics evoke mathematics anxiety? Studies investigating this subject are in conflict (Devine, Fawcett, Szűcs, & Dowker, 2012) and longitudinal studies are still scarce (but see Cargnelutti, Tomasetto & Passolunghi, 2017 and Gunderson et al., 2019). Most plausibly, a reciprocal relationship between both constructs exists, implying that both reinforce one another (Carey, Hill, Devine, & Szücs, 2016; Gunderson et al., 2019).

Several explanations have been proposed for the negative relation between mathematics anxiety and mathematical performance. Maloney and colleagues (e.g., Maloney, Risco, Ansari, & Fugelsang, 2010; Maloney, Ansari, & Fugelsang, 2011) for example suggested that high math anxious individuals suffer from a basic numerical processing deficit (e.g., problems with counting and comparing numbers) that forms the basis of their difficulties with more complex mathematics. According to Eysenck and colleagues (2007), anxiety impairs executive functions that rely on attentional control. For example, the anxiety reaction that is triggered by the confrontation with math-related stimuli might involve worrying intrusive thoughts that consume the limited attentional capacity of the central executive, which are therefore less available for processing the math task (Aschraft & Faust, 1994; Aschraft & Kirk, 2001). A related possibility is that high math anxious individuals suffer from an inability to inhibit attention to these worrying thoughts, and therefore inhibition should be considered as the key to understanding the relationship between worrying thoughts and the reduction in working memory resources (Hopko, Ashcraft, Gute, Ruggiero, & Lewis, 1998; Mammarella, Caviola, et al., 2018; Mammarella, Donolato, et al., 2018).

Metacognition and mathematical performance

Metacognition refers to processes used to monitor and regulate our mental activities (Fleming & Dolan, 2012; Özsoy & Ataman, 2009). Schraw and Moshman (1995) proposed to split up metacognition in two different components. The first component is the *metacognitive knowledge*, which contains all knowledge and insights into our own cognition. Considering metacognitive knowledge, Erickson and Heit (2015), for example, demonstrated in two experiments that students tend to over-estimate their own mathematical performance. In studies investigating (contributing factors of) math performance, this metacognitive knowledge is often alternatively referred to as 'math self-efficacy', i.e. "an individual's confidence in his or her ability to perform mathematics" (Ashcraft & Rudig, 2012, p. 249; see also Lee, 2009). The second component is the *regulation of cognition* which involves the planning, monitoring and evaluation of behavior. In the current work, we are particularly interested in the latter. Decades of research have shown that people with good metacognitive skills more frequently monitor their mental states, regulate their behavior, and implement better strategies. As a consequence of these enhanced metacognitive regulation skills, often better performance on various tasks has been reported (see Bjork et al., 2013, for an overview). For example, having better metacognitive regulation skills has been shown to be beneficial for mathematical performance. In particular, studies have shown that metacognitive skills are positively related to geometry performance, word problem-solving abilities and arithmetic performance (e.g., Lucangeli and Cornoldi, 1997; Jacobse & Harskamp, 2012). Moreover, a large body of research has investigated the metacognitive processes that accompany reasoning, problem-solving, and decision-making tasks (for review, see Ackerman & Thompson, 2017).

Relation between mathematics anxiety, metacognition and mathematical performance

Given the importance of mathematics anxiety and metacognition for mathematical performance, the current study will focus on the interplay between these three measures. Mathematics anxiety and metacognition not only influence mathematical performance, but evidently also influence each other. For instance, it has been demonstrated that students with low mathematics anxiety use more metacognitive regulation (e.g. Jain & Dowson, 2009) and the attribution of failure or success on a test has an effect on anxiety (Bandalos, Yates, Thorndike-Christ, 1995). Despite previous work examining the link between mathematics anxiety and metacognition, their effects on mathematical performance were typically studied in isolation. To our knowledge, there are only a few studies addressing the relation between these three factors. Legg and Locker (2009) measured both mathematics anxiety and metacognition and observed that mathematical performance decreased as mathematics anxiety increased, but that this was not true for participants reporting high levels of metacognitive regulation. In other words, high-metacognitive regulation seems to overcome the detrimental effects of mathematics anxiety. Similarly, Lai, Zhu, Chen and Li (2015) found that the effect of mathematics anxiety on performance was mediated by metacognition. Finally, Erickson and Heit (2015) reported that a group of students who scored relatively high on a mathematics anxiety questionnaire, also over-predicted their scores on math tests—although direct relations between the three constructs were not examined in this study.

Importantly, previous studies on this topic are prone to two shortcomings that hinder their interpretation. First, metacognition is typically measured using questionnaires that assess factors such as planning, checking, monitoring and evaluating. However, whether or not participants who report to actively monitor their performance are also good at this cannot be determined. A participant who claims to frequently monitor his or her behavior might actually make very bad evaluations of his/her own performance. For example, two students might self-report the same level of metacognitive monitoring while studying, but one of them might make very good evaluations of her own knowledge because she constantly tests herself (Karpicke & Roediger, 2008), whereas the other might make very bad self-evaluations by relying on reading fluency as an indication of knowledge (Undorf et al., 2017). Second, previous studies did not take into account whether differences in metacognition might be confounded with differences in mathematical task performance. For example, the *State Metacognitive Inventory* (SMI; O'Neil & Abedi, 1996) measures metacognitive regulation by asking questions such as "I determined how to solve the task problems". When using such questions as a measure of metacognition, one ignores the possibility that it is much easier for participants with excellent mathematical skills to determine how to solve a mathematical task. Thus, this potentially confounds mathematical performance and metacognition (for a formal demonstration of this, see Maniscalco & Lau, 2012). In the current work, both these limitations were overcome by asking participants to evaluate their own performance on each trial using confidence judgments. Furthermore, we used the recently developed meta-*d'* framework (for review, see Fleming & Lau, 2014), which allows to quantify how good participants can estimate their own performance *independent* from their actual performance. Using this approach, it was possible to dissociate the efficiency with which confidence judgments separated correct from erroneous judgments (metacognitive efficiency), and how over- or under-confident participants in general are (metacognitive bias).

The present study

In the present study, we assessed the interrelation between mathematics anxiety, metacognition (both metacognitive efficiency and metacognitive bias), and mathematical performance. Mathematical performance and metacognitive judgments about this performance were quantified using a novel experimental mathematical task. In this task, participants were first briefly presented with a subtraction or multiplication problem of varying difficulty, and indicated how confident they were that they could accurately solve the problem, i.e., a prospective confidence judgment. Next, a solution to the problem was presented and participants were asked to decide as quickly and accurately as possible whether or not the proposed solution was correct. Finally, participants indicated their level of confidence in the decision, i.e., a retrospective confidence judgment. The distinction between prospective and retrospective confidence might be important, as both types of confidence are based on partially different information: whereas prospective confidence is largely based on previous confidence over a longer window (Fleming et al., 2016) and can influence the subsequent decision process (Boldt et al., 2019), retrospective confidence is mostly affected by the speed and accuracy of the preceding decision. Such a comparison of different judgments made across different stages of the task is embedded within a long tradition of relating different metacognitive experiences to memory performance (Leonesio & Nelson, 1990). Our primary focus of interest was whether metacognition could explain additional variance in mathematics anxiety, over and above participants' actual mathematical performance, because of course this insight might be useful when remediating mathematics anxiety (e.g., Foley, Herts, Borgonovi, Guerriero, Levine, & Beilock, 2017). In addition, we examined whether relations between the three constructs differed depending on whether confidence judgments were given prospectively or retrospectively.

Method

Participants

Eighty participants (11 males; mean age = 19.7 years, range: 18–31) took part in return for course credits. Participants were first year bachelor psychology students from the Vrije Universiteit Brussel in Belgium. All participants provided written informed consent before participation. Data of three participants were removed because they performed at chance level (details below), making it unclear whether they understood the task and/or complied with the task instructions. Both the sample size and the analytical plan were pre-registered before the start of data collection. The preregistration form together with the raw data can be found on the Open Science Framework (https://osf.io/fc54x/). This study was approved by the Ethical Committee of the KU Leuven (G-2017 10 951).

Procedure and apparatus

Upon arrival in the lab, participants first performed the pen-and-paper arithmetic number fact test (Tempo Test Rekenen or TTR; De Vos, 1992; see below) in a small group (of max. 14 persons). Afterwards, participants were seated individually in dimly lit cubicles to perform the experimental mathematical task. Stimuli were presented on a 17-inch monitor (60 Hz, spatial resolution = 1280 × 1024) located approximately 75 cm from the subject. Stimulus presentation and response registration was controlled by E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). After performing the experimental mathematical task, participants filled out the mathematics anxiety questionnaire (see below) while remaining seated in their cubicles.

Materials

Subtraction and multiplication experimental task.

Participants were presented with 264 arithmetic problems. There were nine different types of assignments (four types of subtractions: xx-x, xx-xx, xxx-xx and xxx-xxx that each appeared with and without carry-over; and three types of multiplications: xx*x, x*xx and xx*xx), with eight exercises per type of assignment. Each assignment appeared three times: once with the correct answer (e.g., 63–45 = 18 or 20 × 42 = 840) and twice with an incorrect answer (i.e. for the subtractions once with an error in the decade, e.g., 63–45 = 28, and once with an error in the unit, e.g., 63–45 = 12; for the multiplications once with a table-related error, e.g., 20 × 42 = 860, and once with a random, table-unrelated error, e.g., 20 × 42 = 842). Figure 1 shows an example trial. After a fixation cross for 1 s, a math assignment was shown for 1 s. Afterwards, participants indicated how confident they were that they could accurately solve this equation. Participants indicated their level of prospective confidence using a 6-point confidence scale with labels "certainly wrong", "probably wrong", "maybe wrong", "maybe correct", "probably correct", and "certainly correct" (reversed order for half of the participants), via the six numerical keys at the top of their AZERTY keyboard (1, 2, 3, 8, 9 or 0), which were mapped onto the six confidence levels. After a blank of 250 ms, the same assignment as before was shown together with a solution. Participants were instructed to decide as quickly and accurately as possible whether this was the correct or the incorrect solution for this assignment by pressing 'c' or 'n' (reversed order for half of the participants) with the thumbs of both hands. The response deadline was set to 3 s. After their response, a blank screen was shown for 250 ms after which participants indicated their level of retrospective confidence in having made the correct decision.

The main part of the experiment comprised 6 blocks of 44 trials each. The experiment started with 10 practice trials in which participants were only shown an assignment and solution and decided whether the solution was correct or not. On these trials, they received error feedback with regard to their performance. Afterwards, participants performed 10 practice trials that were identical to the main part. Finally,

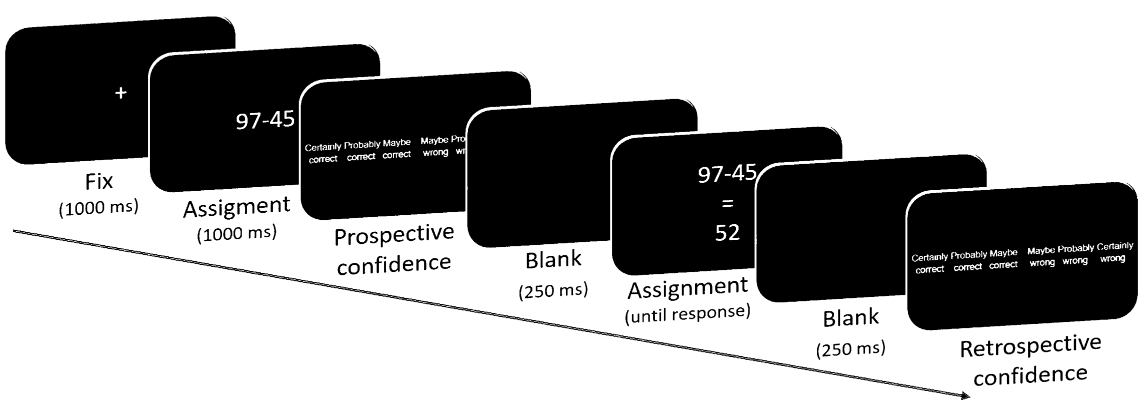

Fig. 1 Example of an experimental trial. After a brief presentation of a mathematical assignment on the screen, participants indicated how confident they were that they would accurately judge the solution to this problem. Afterwards, the assignment was shown again together with a proposed answer. Participants indicated as fast and accurate as possible whether the proposed answer was correct or not. Finally, they indicated their level of confidence in their decision

participants performed a last practice block of ten trials in which they were motivated to make their prospective confidence judgments based on intuition, this way discouraging them to actively calculate the answer to the assignment. Hereto, a 3 s response deadline for the prospective confidence judgments was set in this block.

Mathematics anxiety

We measured mathematics anxiety using the Dutch translation of the pen-and-paper Abbreviated Math Anxiety Scale (AMAS; Hopko, Mahadevan, Bare, & Hunt, 2003). The AMAS comprises nine items questioning how the participants thinks (s)he would feel in a certain math-related situation (e.g., taking a math exam). Responses are indicated on a 5-point Likert-type scale, ranging from 1 (low anxiety) to 5 (high anxiety). The total score represents the sum of the nine items (score ranging from 9 to 45, with higher scores indicating higher levels of mathematics anxiety). Although no data on the reliability and validity of the Dutch version of the AMAS have been reported, diverse foreign studies using translated versions of the AMAS have shown the transcultural character of this questionnaire (e.g., Cipora, Szczygiel, Willmes, & Nuerk, 2015; Primi, Busdraghi, Tomasetto, Morsanyi, & Chiesi, 2014; Schillinger, Vogel, Diedrich, & Grabner, 2018). For this sample, internal consistency measured using Cronbach's α for the total score was 0.86.

Mathematical decision-making

To control whether our experimental task gave a reliable index of the participants' mathematical performance, we included a control standardized pen-and-paper math test. The arithmetic number fact test (Tempo Test Rekenen or TTR; De Vos, 1992) contains 200 simple arithmetic number fact problems presented in 5 columns (from left to right: addition, subtraction, division, multiplication, and mixed problems) of 40 items with an increasing difficulty level. Participants received 30 s per column, to solve as many problems as possible within a column. Their total score (out of 200) was the number of correct answers. The TTR is a standardized arithmetic test that is frequently used in the Flemish education system. For this sample, Cronbach's α was 0.92.

Quantifying task performance, metacognitive efficiency and confidence bias

Basic task performance was quantified by calculating *d'*, a measure of task performance that is insensitive to differences in response bias (Green & Swets, 1966). This was particularly important in the current experiment, because the answer 'correct' was the accurate answer on 67% of the trials. To evaluate whether performance was different from chance level (i.e., $d' > 0$), a null distribution was simulated separately for each participant by randomly shuffling the responses before computing *d'*. This was repeated 5000 times for each participant. Only if the actual *d'* was larger than 95% of the values in the null distribution, it can be concluded that performance significantly differed from chance level. Based on this procedure, data of three participants were excluded. We then computed meta-*d'* values, which quantify the extent to which confidence ratings discriminate between correct and incorrect responses, while controlling for their first-order performance (Maniscalco & Lau, 2012). By dividing meta-*d'* by *d'*, we obtained *M*-ratios, which quantify *metacognitive efficiency*. When this ratio is 1, all available first-order information is used in the confidence judgment. When the ratio is smaller than 1, metacognitive efficiency is suboptimal, meaning that not all available information from the first-order response is used in the metacognitive judgment (Fleming & Lau, 2014). Although this measure is typically quantified with retrospective confidence, its interpretation is similar when quantifying it with prospective confidence. If the ratio is 1, all information used for the confidence judgment was also used to solve the mathematics assignment; if the ratio is smaller than 1, less information was used for the confidence judgment than for the mathematics assignment (e.g. because of additional processing of the assignment after the confidence report); if the ratio is larger than 1, some information that was used for the confidence judgment is not used to solve the mathematics assignment (e.g., the number of elements in an assignment can inform prospective confidence, but this information cannot be used to solve the assignment). Finally, *confidence bias* was quantified as the average level of confidence on correct trials only. Only correct trials were taken into account, to avoid influences of average accuracy level on this measure. Note that both metacognitive efficiency and confidence bias were calculated separately for prospective and retrospective confidence judgments.

Statistical analysis

Behavioral data were analyzed using linear mixed models, because these allow data analysis at the single-trial level. Random intercepts for each participant were fitted and error variance caused by between-subject differences was accounted for by adding random slopes to the model. The latter was done only when this increased the model fit, as assessed by model comparison. Accuracy was analyzed using logistic linear mixed models, for which X^2 statistics are reported. RTs and confidence were analyzed using linear mixed models, for which *F* statistics are reported and the degrees of freedom were estimated by Satterthwaite's approximation (Kuznetsova et al., 2014). Model fitting was done in R (R Development Core Team, 2008) using the lme4 package (Bates et al., 2015). Statistical evaluation of robust regression coefficients was done using robust F-test for multiple coefficients from the sfsmisc package (Maechler, 2018). Mediation analyses were performed at the subject level using the mediation package (Tingley et al., 2014). Estimates for the mediation effect in the models featuring prospective and retrospective confidence were then compared to each other using a paired t-test.

Results

Task performance and confidence

Subtraction. Summary measures of accuracy, reaction times and confidence as a function of the number of elements in the assignment are shown in Fig. 2. A logistic mixed regression model was fit in which accuracy was predicted by the type of assignment, operationalized via the number of elements in the assignment (e.g., 3 in case of an assignment of the type xx-x; and similarly for 4, 5 and 6). The effect of assignment type was significant, $X^2(3) = 820.41$, $p < 0.001$. Follow-up comparisons showed that accuracy was higher in three-digit ($M = 86.0\%$) than four-digit assignments ($M = 64.5\%$), $z = 20.61$, $p < 0.001$, higher in four-digit than in five-digit assignments ($M = 57.3\%$), $z = 6.15$, $p < 0.001$, whereas the five-digit and six-digit assignments ($M = 57.0\%$) did not differ from each other, $p = 0.618$. A similar mixed regression model fitting RTs on correct trials showed a similar main effect of assignment type, $F(3,75.84) = 12.33$, $p < 0.001$. Follow-up comparisons showed that RTs were faster in three-digit ($M = 1367$ ms) than four-digit assignments ($M = 1584$ ms), $z = 5.55$, $p < 0.001$, higher in four-digit than in five-digit assignments ($M = 1699$ ms), $z = 2.36$, $p = 0.018$, whereas the five-digit and six-digit assignments ($M = 1644$ ms) did not differ from each other, $z = -1.69$, $p = 0.090$.

Separate mixed regression models predicting either prospective or retrospective confidence by assignment type showed similar main effects: prospective confidence: $F(3,75.2) = 97.36$, $p < 0.001$; retrospective confidence: $F(3,75.37) = 136.36$, $p < 0.001$. Follow-up comparisons showed that prospective confidence was higher in three-digit ($M = 5.05$) than four-digit assignments ($M = 4.19$), $z = 13.55$, $p < 0.001$, higher in four-digit than in five-digit assignments ($M = 3.79$), $z = 9.14$, $p < 0.001$, and higher in five-digit than in six-digit assignments ($M = 3.36$), $z = 7.98$, $p < 0.001$. Likewise, retrospective confidence was higher in three-digit ($M = 5.32$) than four-digit assignments ($M = 4.43$), $z = 14.11$, $p < 0.001$, higher in four-digit than in five-digit assignments ($M = 4.03$), $z = 8.93$, $p < 0.001$, and higher in five-digit than in six-digit assignments ($M = 3.36$), $z = 7.72$, $p < 0.001$.

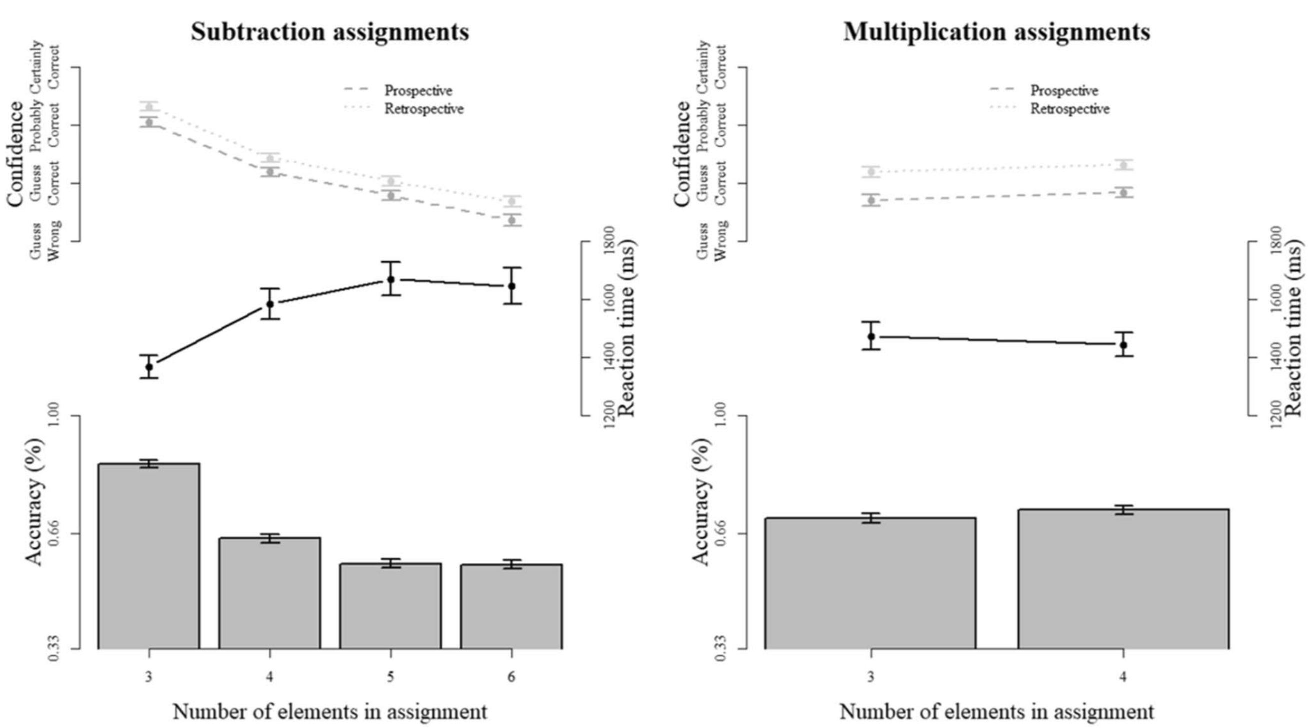

Fig. 2 Accuracy, reaction times and confidence as a function of the number of elements in the assignment. Error bars reflect standard error of the mean

Multiplication. Similar analyses as for subtraction were performed on the multiplication data, were the assignment could consist of either three or four elements. Accuracy in the multiplication task did not differ between three-digit and four-digit assignments ($M = 70.3\%$ vs. $M = 72.7\%$), $X^2(1) = 3.18$, $p = 0.075$, and the same was true for RTs on correct trials ($M = 1473$ ms vs. 1443 ms), $F(1,72.10) = 1.68$, $p = 199$. Likewise, confidence was not different between three-digit and four-digit assignments, neither in prospective confidence ($M = 3.70$ vs. $M = 3.84$), $F(1,78.13) = 3.61$, $p = 0.061$, nor in retrospective confidence ($M = 4.19$ vs. $M = 4.31$), $F(1,76.13) = 1.87$, $p = 0.175$.

From the above, it is clear that our multiplication manipulation failed to affect performance and confidence. This was additionally confirmed by the Pearson correlations between the performance on the experimental task (*d'*) and the performance on our control pen-and-paper math test (TTR): Whereas there was a significant relation between *d'* for subtraction assignment and the TTR subtraction subscale, $r(75) = 0.23$, $p = 0.050$, this was not the case for *d'* for multiplication and the TTR multiplication subscale, $r(75) = 0.06$, $p = 0.609$. One possibility is that the multiplication task was simply experienced as too difficult, as reflected by the fact that the majority of these trials were labeled as 'guess correct'. Therefore, in the remainder, only the data of subtraction assignments will be reported.

The relation between confidence and accuracy

In Fig. 3, the relationship between accuracy and confidence is shown, separately for prospective and retrospective confidence judgments. A logistic mixed regression model was fit in which accuracy was predicted by both types of confidence judgments. Both the main effects of prospective confidence, $X^2(1) = 31.21$, $p < 0.001$, and retrospective confidence, $X^2(1) = 233.10$, $p < 0.001$, were significant, showing that both types of confidence had unique explanatory value in predicting accuracy. Interestingly, after the variable assignment type was entered into this model (which significantly predicted accuracy: $X^2(1) = 192.28$, $p < 0.001$), prospective confidence no longer predicted accuracy, $p = 0.72$, whereas the effect of retrospective confidence remained unchanged, $p < 0.001$. This suggests that prospective confidence judgments were (largely) based on easily available cues, such as the number of elements in an assignment, whereas retrospective confidence also captures information about the actual accuracy of a decision. To formally assess this difference, mediation analyses were performed separately for each participant testing the hypothesis that the relation between confidence and accuracy is mediated by the number of elements. Separate models were fit for retrospective and prospective confidence. As expected, the mediating effect of number of elements was significantly larger for prospective than for retrospective confidence, $t(76) = 8.69$, $p < 0.001$. Figure 3 further shows that retrospective confidence judgments were more sensitive to accuracy than prospective confidence judgments. Mean accuracy was above chance level performance for all levels of prospective confidence, $ps < 0.035$, except for trials judged as certainly wrong, $p = 0.111$. For retrospective confidence judgments, however, mean accuracy was above chance level performance for the tree highest levels of confidence, all $ps < 0.025$, whereas it was significant *below* chance level for trials judged as certainly wrong, $p < 0.001$.

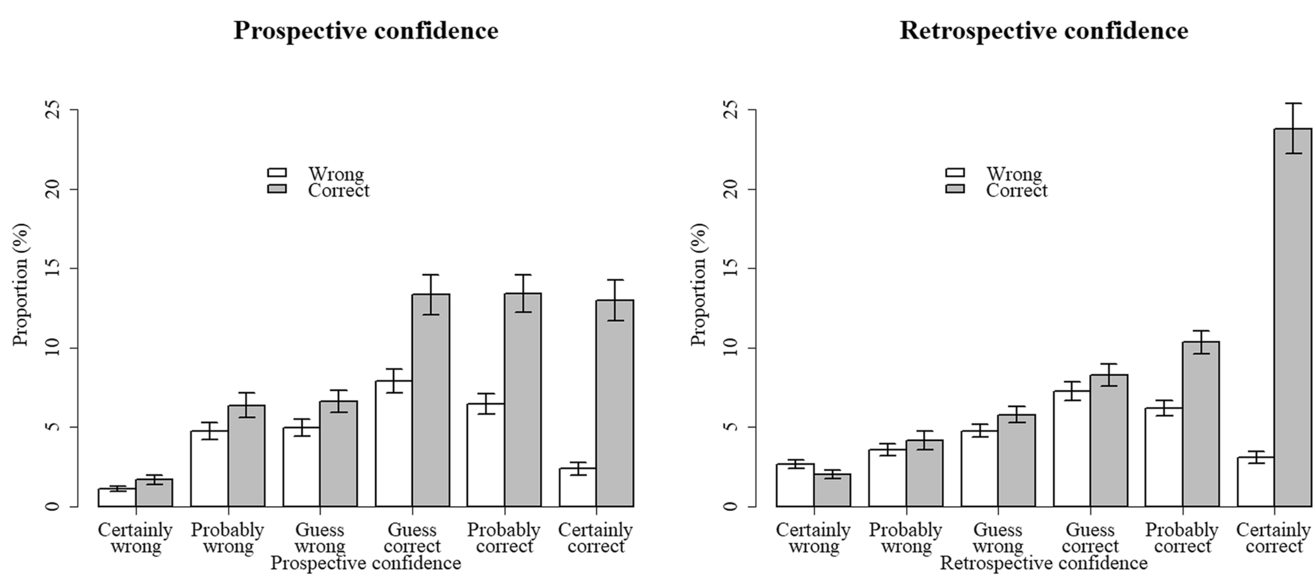

Fig. 3 Relationship between accuracy and decision confidence. Error bars reflect standard error of the mean

To formally asses this differential sensitivity of both types of confidence, we next analyzed *M*-ratios, which quantify the efficiency of metacognitive judgments. In line with the previous analysis, metacognitive efficiency was significantly smaller for prospective confidence judgments ($M_{\text{M-ratio}} = 1.28$) than for retrospective confidence judgments ($M_{\text{M-ratio}} = 1.88$), $t(76) = 4.31$, $p < 0.001$.

Multiple regression analysis

Due to large correlations between prospective and retrospective measures (up to $r = 0.78$), it was not possible to enter all variables into a single model (VIFs > 3; note that these measures are on the participant level, whereas the previous analyses was performed at the trial level). Therefore, we first averaged both prospective and retrospective metacognitive efficiency and confidence bias. Then, a multiple regression model was fitted in which mathematics anxiety was predicted by *d'*, average metacognitive efficiency and average confidence bias (results are presented in Table 1). This analysis showed a significant positive relation between mathematics anxiety and average metacognitive efficiency, $b = 1.49$, $t(73) = 2.17$, $p = 0.033$, and a significant negative relation between mathematics anxiety and average confidence bias, $b = -4.16$, $t(73) = 3.17$, $p = 002$. The relation between *d'* and mathematics anxiety was not significant, $p = 0.156$. The partial relationship between mathematics anxiety and each of these predictors is shown in Fig. 4. To assure that these findings were not driven by outliers, we also conducted separate robust linear regressions. Again, there were significant effects of average metacognitive efficiency, $F(1,73) = 3.96$, $p = 0.050$, and of average confidence bias, $F(1,73) = 7.27$, $p = 0.009$, but not of *d'*, $F(1,73) = 1.51$, $p = 0.223$.

Next, the same regression model on mathematics anxiety was fit separately for prospective and retrospective confidence judgments. There was a significant effect on mathematics anxiety of prospective metacognitive efficiency, $b = 1.94$, $t(73) = 2.86$, $p = 0.005$, and prospective confidence bias, $b = -2.78$, $t(73) = -2.48$, $p = 0.015$, but not

Table 1 Multiple regression predictors of mathematics anxiety

	Average confidence (prospective + retrospective) estimate (SE)	Prospective confidence estimate (SE)	Retrospective confidence estimate (SE)
Performance (*d'*)	3.04 (2.12)	1.61 (1.98)	4.52 (2.27)
Metacognitive efficiency (M-ratio)	1.49 (0.69)*	1.94 (0.68)**	0.69 (0.53)
Confidence bias	–4.16 (1.31)**	– 2.78 (1.12)*	– 5.28 (1.39)***

*$p < .05$; **$p < .01$; ***$p < .001$

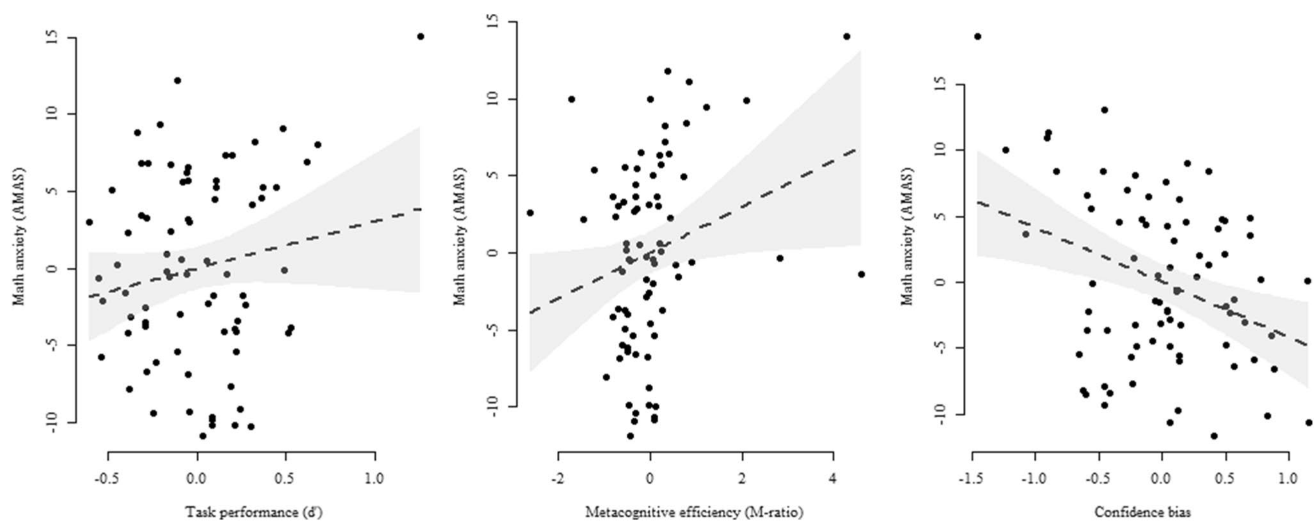

Fig. 4 Partial regression plots showing the partial linear relation between mathematics anxiety and each of the predictors (averaged over prospective and retrospective confidence), while controlling for the other predictors. Note that the partial regression lines always run through the origin (0, 0) because the data in each subplot represent the relation between math anxiety and that specific variable after controlling for the other two variables

of performance, $p = 0.418$. With regard to the retrospective confidence judgments, mathematics anxiety was only significantly predicted by retrospective confidence bias, $b = -5.28$, $t(73) = -3.79$, $p < 0.001$, but not by performance *d'*, $p = 0.050$, or by retrospective metacognitive efficiency, $p = 0.201$. To formally compare the significant slope for prospective metacognitive efficiency to the non-significant slope for retrospective metacognitive efficiency, we computed a z score using the formula in Eq. 4 in Paternoster et al. (1998). This showed that the difference in slopes between both types of confidence just failed to reach significance, $z = 1.45$, $p = 0.074$. Finally, we note that the difference between retrospective and prospective confidence, when calculated separately per participant, did not correlate with mathematical anxiety scores, $r(75) = -0.15$, $p = 0.177$. Also the proportion of trials where retrospective confidence was higher than prospective confidence, calculated separately per participant, was unrelated to mathematical anxiety, $r(75) = -0.004$, $p = 0.166$.

Discussion

We investigated the relationship between mathematics anxiety, metacognition and mathematical performance. We were mainly interested in whether metacognition could explain additional variance in someone's level of mathematics anxiety, on top of his/her actual mathematical performance. Having insight in these interrelationships might be particularly important in the context of remediating mathematics anxiety, which might in turn be useful with regard to the worldwide need for more workers with degrees in science, technology, engineering, or mathematics (STEM). In our experimental mathematical task, participants had to indicate their level of confidence with regard to subtraction problems comprising a varying number of elements (i.e., a manipulation of task difficulty), prior to and after judging whether a proposed solution was correct or not. Both prospective and retrospective confidence judgments predicted unique variation in accuracy, however, the explanatory effect of prospective confidence disappeared after taking task difficulty into account. This suggests that prospective, but not retrospective, confidence is largely based on easily available cues indicative of performance. Results of a multiple regression analysis indicated that individual differences in mathematics anxiety were negatively related to the overall level of *confidence* (both prospectively and retrospectively), and positively related to metacognitive *efficiency* (only prospectively). In the remainder, we discuss the interpretation and implications of the current findings.

Mathematics anxiety and metacognitive bias

A robust finding for both prospective and retrospective confidence judgments is that they were negatively related to individual differences in mathematics anxiety. Specifically, participants who were math anxious expressed lower confidence in both their ability to solve an upcoming mathematical problem and after having solved the mathematical problem. As discussed in the introduction, the causal direction of the relation between mathematics anxiety and mathematics performance is still debated, but one reasoning is that mathematics anxiety results in part from experiences of failure in math. Therefore, it could be that experiences of failure and the salience of such experiences (and hence the plausibility of developing math anxiety) may be greater for people who are more aware of their difficulties in solving mathematics problems while doing so, and do not depend just on test scores to know when they are failing. Indeed, general confidence, also referred to as 'self-esteem', has always been closely associated with anxiety (Çivitci & Çivitci, 2009; Harmon-Jones et al. 1997). Moreover, recently, two studies examined the relation between self-esteem and math anxiety in particular. In line with our findings, Mammarella, Caviola, et al. (2018), Mammarella, Donolato, et al. (2018)) observed a negative relation between both constructs in elementary school children and Xie et al. (2018) showed that the way in which self-esteem affects math anxiety differs for male vs female high school students. Using structural equation modeling, the latter authors demonstrated that for young men, self-esteem had both a direct effect on math anxiety, and it had indirect effects on math anxiety through control beliefs, test anxiety, and general anxiety. For young women, self-esteem only affected math anxiety through test anxiety and general anxiety, but not directly. However, again, in those previous studies, confidence or self-esteem was indexed via questionnaires, making the results susceptible to all problems reported in that regard in the introduction. Using the meta-*d'* framework, we were able to quantify the average level of confidence (i.e., metacognitive bias), independently from how accurate confidence judgments are and how accurate participants are (i.e., mathematical performance). Therefore, the current study provides a first piece of evidence that the relation between mathematics anxiety and average confidence (metacognitive bias) cannot be explained by differences in performance or metacognitive efficiency. Similarly, Sokolowski et al. (2019) showed that university students' *perceived math ability*—which can be considered as a proxy for metacognitive bias—correlates stronger with math anxiety than their actual math ability. However, again, these authors did not make use of the meta-*d'* framework and therefore did not dissociate between metacognitive bias and metacognitive efficiency. This negative relation between general confidence and math anxiety might explain why students with math anxiety tend to *avoid* math-related education (e.g., Ashcraft & Moore, 2009). Indeed, especially the prospective confidence—based on easily available cues—might be at play here: Because students with higher levels of reported math anxiety have a lower confidence in their ability to solve upcoming mathematical problems, they might avoid them especially when those math problems seem to be difficult, as is presumably the case in education that focuses on, or emphasizes math (e.g. STEM education). Consequently, this negative interrelationship between math anxiety and lower confidence might have serious consequences for participation in STEM education. Future research might therefore want to focus on enhancing students' confidence/self-esteem with regard to mathematics to remediate mathematics anxiety and/or mathematical difficulties. Notably, participants in the current study were all undergrad psychology students, and therefore might not be representative for the entire population. Specifically, these participants might have more experience with testing and examination. Therefore, future studies should aim to examine whether the current findings can be replicated in a larger and more representative sample. Finally, one could argue that the observed negative relation between general confidence and math anxiety is not math-specific, but more general in nature. Confidence and (general) anxiety have indeed been shown to be associated in previous work. Recently, Rouault and colleagues even demonstrated this relationship making use of the meta-d' framework (Rouault et al., 2018). In line with our observations, these authors also reported a negative relation between (a symptom dimension related to) anxiety and metacognitive bias in a visual task. In the current study, we however believe that instead of general anxiety, we actually indexed math anxiety and the observed link is thus indeed math-specific, and this for two reasons. First, during the whole experiment, the math-related content was omnipresent and emphasized a lot to the students (they had to complete two math tasks and were asked about how nervous they were about math). Second, many previous studies have shown that although math anxiety might overlap with constructs like test anxiety and general anxiety, it cannot be reduced to these constructs and really seems to be a separate entity (Dew & Galassi, 1983; Dowker, Sarkar, & Looi, 2016; Hembree, 1990; see also a review by Ashcraft & Ridley, 2005).

Mathematics anxiety and metacognitive efficiency

In recent years, a growing number of studies have harnessed the meta-*d'* framework to examine relations between metacognitive efficiency and related constructs. For example, metacognitive efficiency was found to be impaired in high-compulsive participants (Hauser, Allen, Rees, & Dolan, 2017; Rouault et al., 2018), increased in a symptom dimension related to anxiety and depression (Rouault et al., 2018), and positively related to executive control (Drescher et al., 2018). In the current study, it was found that individual differences in mathematics anxiety were positively related to how well participants could estimate their own performance (i.e., metacognitive efficiency). Thus, participants with higher levels of mathematics anxiety were actually better at judging their own accuracy. At first sight, this relationship seems unexpected (but see Rouault et al., 2018), given that some previous work has documented a negative relation between mathematics anxiety and self-reported metacognition (Legg & Locker, 2009). However, as explained before, previous studies on this topic largely relied on questionnaires assessing the extent to which participants experienced that they monitored and regulated their own behavior, which does not imply that they also accurately did so. In contrast, in the current work we were able to quantify metacognitive efficiency independent of the actual mathematical performance (Fleming & Lau, 2014). When dissociating between the two types of confidence judgments, it is intriguing that only a positive relation was observed between mathematics anxiety and prospective confidence judgments, whereas the relation between mathematics anxiety and retrospective confidence failed to reach significance. This seems to imply that participants with high mathematics anxiety are not actually better at evaluating their own performance, but rather, they are better at predicting whether or not they will correctly solve a trial. Interestingly, the relation between prospective confidence and response accuracy vanished after controlling for the number of elements in the mathematical problem. This suggests that prospective confidence is largely based on easily available cues, such as the apparent difficulty of a problem. From this, it follows that high math anxious participants are better in predicting which type of mathematical problems they will be able to complete successfully and which ones not. From the perspective of the attentional control theory (Eysenck et al., 2007), this finding might be explained by the fact that the high math anxious participants could have paid *more attention* to the 'cued' assignments, because their math anxiety created an attentional bias toward the for them 'threat-related' math stimuli (see also Rubinsten et al., 2015).

Differences in prospective versus retrospective confidence

Most work in the domain of decision confidence has focused on the question how participants construct a confidence judgment after they have made a choice. The emerging answer from both empirical and theoretical work is that confidence judgments reflect the probability of a response being correct (Kepecs et al., 2008; Kiani & Shadlen, 2009), which is computed by evaluating the strength of the evidence for a response (Gherman & Philiastides, 2018; Maniscalco et al., 2016) and response speed (Kiani et al., 2009). Interestingly, it remains largely unknown how prospective confidence judgments are constructed. Although one might argue that, given the large correlation between prospective and retrospective confidence, it is questionable whether both these variables really reflect different things, we saw clear qualitative differences between both type of judgments in our data. Most clearly, only retrospective but not prospective judgments predicted below-chance performance when participants indicated to have committed an error; reversely the predictive effect on accuracy disappeared for prospective, but not retrospective confidence, after taking into account the number of elements in the equation. Moreover, recent work has argued that prospective confidence might be calculated in a different way than retrospective confidence. For example, Fleming and colleagues (2017) showed that prospective confidence is largely influenced by previous confidence over a longer time window. In line with these findings, a potential explanation for the current results is that with experience, participants learn that assignments with a high number of elements are typically associated with low performance. Consequently, when probed for a prospective confidence judgment, participants rely on this predictive information to estimate the accuracy of an upcoming choice. Such a mechanism is consistent with recent claims that metacognitive judgments are based on cues that are indicative of performance (Boldt et al., 2017; Desender et al., 2017; Koriat, 1997). One might argue that collecting both prospective and retrospective measures of confidence within the same experiment could be problematic because they might influence each other. However, participants likely experience different levels of retrospective and prospective confidence during task execution, regardless of whether they are queried about it. Therefore, we believe that collecting both measures in the same experiment is beneficial as it provides insight into the specific relationship between both.

Conclusion

In the current work, individual differences in mathematics anxiety were found to be negatively related to overall confidence level and positively to metacognitive efficiency. These finding might have import implications concerning the promotion of participation in STEM education.

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Declairations

Conflict of interest Both authors declare to have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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