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Arithmetic operations without symbols are unimpaired in adults with math anxiety

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Abstract

This study characterises a previously unstudied facet of a major causal model of math anxiety. The model posits that impaired "basic number abilities" can lead to math anxiety, but what constitutes a basic number ability remains underdefined. Previous work has raised the idea that our perceptual ability to represent quantities approximately without using symbols constitutes one of the basic number abilities. Indeed, several recent studies tested how participants with math anxiety estimate and compare non-symbolic quantities. However, little is known about how participants with math anxiety perform arithmetic operations (addition and subtraction) on non-symbolic quantities. This is an important question because poor arithmetic performance on symbolic numbers is one of the primary signatures of high math anxiety. To test the question, we recruited 92 participants and asked them to complete a math anxiety survey, two measures of working memory, a timed symbolic arithmetic test, and a non-symbolic "approximate arithmetic" task. We hypothesised that if impaired ability to perform operations was a potential causal factor to math anxiety, we should see relationships between math anxiety and both symbolic and approximate arithmetic. However, if math anxiety relates to precise or symbolic representation, only a relationship between math anxiety and symbolic arithmetic should appear. Our results show no relationship between math anxiety and the ability to perform operations with approximate quantities, suggesting that difficulties performing perceptually based arithmetic operations do not constitute a basic number ability linked to math anxiety.

Keywords

Mathematics anxiety; numerical cognition; arithmetic; symbolic; non-symbolic

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Introduction

Humankind has made incredible advances due to the development of formal mathematical structures. However, on an individual level, many view engaging with math as a monumental struggle, and we do not have a clear understanding of how those negative feelings come into being. Math anxiety (MA) is defined as feelings of tension or dread when confronted with the need to perform mathematics (Ashcraft & Faust, 1994; Richardson & Suinn, 1972). It is a widespread phenomenon that affects the individual in myriad ways. Hart and Ganley (2019) found that about half of US adults score at moderate to high levels of MA with women reporting meaningfully higher levels than men. They found no such differences between different racial and ethnic groups (Hart and Ganley, 2019). In the long term, MA affects career prospects: those whose MA levels increase or are high during schooling are less likely to choose STEM careers (Ahmed, 2018), and those

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in STEM careers report lower levels of MA (Hart and Ganley, 2019; Hembree, 1990).

One model to explain MA places difficulties in basic number skills—such as counting or number comparison—that relate to downstream mathematic abilities as the primary precursor to developing MA (Beilock & Maloney, 2015; Maloney, 2016). Under this "reduced capacities" model, some individuals have reduced cognitive competencies that lead to lower math performance and the development of MA. Lending credence to this model are studies showing that people with high MA perform poorly on simple numerical tasks, such as enumeration and number comparison (Maloney et al., 2010, 2011). This model is compelling, as the causal mechanism is straightforward and intuitive. These skills are fundamental, so a weaker foundation may naturally lead to less stable future development.

Despite the emphasis placed on its position in the model, "basic number skills" remains underdefined. Theories of numerical cognition assert that one of the most basic skills for representing number is based on the evolutionarily ancient system that we share with many animals (Dehaene, 2011). The so-called approximate number system (ANS) is thought to enable the representation of numerosities, or the number of items in a set, and is posited to serve as a foundation for mathematical competence (Odic & Starr, 2018). Whether these perceptually based, approximate, non-symbolic, magnitude representations *directly* drive the acquisition of precise, symbolic mathematics has been hotly debated (Bugden et al., 2016, 2021; Merkley et al., 2017; Szkudlarek & Brannon, 2017; J. Wang et al., 2017). Regardless of that debate, however, empirical studies especially in children do show a meaningful association between one's performance in tasks involving non-symbolic magnitude representations and tasks involving symbolic magnitude representations (Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2017). Thus, understanding to what extent non-symbolic magnitude processing relates to MA could uncover the cognitive mechanisms underlying MA.

Hence, the ANS has received much attention in the MA literature; however, the results so far are mixed (Colomé, 2019; Dietrich et al., 2015; Hart et al., 2017; Lee & Cho, 2018; Lindskog et al., 2017; Maldonado Moscoso et al., 2020; Núñez-Peña & Suárez-Pellicioni, 2014). For example, Dietrich and colleagues (2015) found no relation in an adult population between MA and performance on a non-symbolic dot comparison task (judge which set of dots has a larger numerosity), as measured by error rate and response time (RT), nor did they find relations between MA and the Weber fraction, a calculated measure of ANS acuity. Likewise, Colomé (2019) replicated and extended this effect by finding no group difference (low vs high MA) on the dot comparison task when the size of the dots could facilitate (i.e., the larger numerosity set has large dots) or hinder (i.e., the larger numerosity set has small dots) choosing the larger numerosity. Notably, there is a lack of research on the relation between numerosity processing and MA in early schooling, but to our knowledge, the youngest age group tested (ages 9–15) showed no correlation between MA and numerosity discrimination (Z. Wang et al., 2015). In contrast, Lindskog and colleagues (2017) found that, in adults, MA was significantly negatively correlated with accuracy on the dot comparison task and that MA fully mediated the relationship between dot comparison accuracy and math performance.

The literature, thus, is inconclusive, as adults with high MA do not show consistent differences compared with those with low MA on this purported "building block" of numerical thinking. One explanation is that those with high MA start with low ANS acuity but make gains to end up on par with their low-MA counterparts over the course of development, although this is unlikely given the relative stability of ANS acuity (Elliott et al., 2019; Purpura & Simms, 2018) and would not be entirely consistent with the findings of Maloney et al. (2010), where adults with MA were slower to enumerate objects. A more plausible explanation is that using ANS to solve a given magnitude-related task does not qualify as "basic number skills" despite claims that ANS-based abilities underlie future math performance (e.g., J. Wang et al., 2017). That said, performing dot comparison utilises limited aspects (i.e., estimation and comparison) of primitive skills recruiting non-symbolic magnitude representations. Indeed, research in the past decade or so has identified that the ANS enables not only estimation and comparison of numerosities but also operations (akin to arithmetic operations) of numerosities (Barth et al., 2006; McCrink & Wynn, 2004; Park & Brannon, 2013, 2014). Non-symbolic estimation and comparison tasks widely tested in previous studies lack the *operational* component that may more closely relate to the impaired abilities of those with MA. Although ANS acuity may be similar between those with high and low MA, it is yet unknown if any impairment extends to ANS functions beyond simple magnitude processing, such as performing operations with non-symbolic quantities.

On the contrary, MA consistently relates to performance on tasks and processes requiring precise representations of numerical symbols. The most widely studied of these is symbolic arithmetic, in which those with high MA perform consistently worse than their low-MA counterparts (Barroso et al., 2020; Hembree, 1990; Ma, 1999). However, prior literature suggests both context and content of numerical symbols influence MA-related performance, beyond the clear relation to classroom math performance. For example, those with high MA struggle with representing numerical symbols even when not performing number processing, as evidenced by lower performance in digit (but not letter) span (Witt, 2012). Furthermore, previous work has indicated that adults with high MA demonstrate an attentional bias to numerical symbols and math-related words, as evidenced by performance in the dot probe task (Rubinsten et al., 2015) and numerical Stroop task (Suárez-Pellicioni et al., 2015). Taken together, these data indicate that MA disrupts far more than performance in math as is traditionally taught in school. Instead, MA seemingly relates to a wide array of processes involving the precise representation information that is numerical in nature, even if not used as such in context.

To date, many studies that show differences between high and low MA groups contain two confounded constructs that may contribute to said differences. First is the usage of operations. Arithmetic operations are widely studied, and impaired ability to perform operations could, in theory, be a precursor that leads a student to perform worse in early math courses and develop MA. Second is the usage of symbols or precise representations. We operationalised symbols and precise representations in contrast to the approximate nature of the ANS. For example, enumerating a series of objects (as in Maloney et al., 2010) may not use Arabic numerals, but requires a precise representation of the magnitude in the form of a verbal numeral, and thus is symbolic. In contrast, an ANS-based comparison task is based on a non-precise, noisy representation of numerical value and is dependent on ratio (Feigenson et al., 2004), and thus is not symbolic. The idea that precise representations relate to MA connects evidence on attentional bias and other tasks that show MA differences in the absence of math. Research on symbols without mathematical operations has been fruitful, especially those studies involving math words as distractors (e.g., Hopko et al., 1998), but the question remains whether performing operations without symbols leads to differences among those with high and low MA.

The aim of our study is to tease apart the relationship between MA and its deleterious effects on performance at the operation and stimulus level. To do so, we modified an established non-symbolic arithmetic test (similar to Park & Brannon, 2014) to include a production component. The purpose of this modification was to bring this task more in line with the symbolic arithmetic test and make them both production tasks. In some trials of this modified task, participants watched as two quantities of dots appeared and moved behind an opaque occluder simulating addition. In other trials, one set of dots entered the occluder, and a second set exited, simulating subtraction. Participants then had to manipulate a dot array to match their representation of the total numerosity of dots behind the occluder. Thus, this task involved approximate arithmetic. All participants also completed a symbolic arithmetic test.

We hypothesised that if operations involving numeric quantities is a primitive skill disrupted in MA, both approximate arithmetic and symbolic arithmetic performance should relate to MA status. However, if MA deficits are related specifically to symbolic processing, then only symbolic arithmetic should relate to MA status. Symbolic arithmetic is known to be strongly related to both of spatial and verbal working memory capacities (Caviola et al., 2020; Szűcs et al., 2014). In addition, approximate arithmetic is also thought to involve spatial, but not verbal, working memory in the form of manipulation of visual items (Park & Brannon, 2014). Thus, we included both a spatial 2-back task (i.e., maintain and update the location of a dot's position in an array across multiple trials) and a verbal 2-back task (i.e., maintain and update the identity of a letter across multiple trials) to account for individual differences in working memory as nuisance variables in our regression analyses. That is, these measures were used as covariates in a regression analysis to remove any effect of these more domain-general capacities in assessing the relationship between MA and arithmetic performance.

Methods

Participants

A total of 92 undergraduates (female = 72; ages 18–24) from the University of Massachusetts Amherst were recruited for participation. In total, 83 undergraduates (female = 71, ages 18–24) were included in the final analysis. The largest racial group were White participants ($n = 50$), followed by Asian participants ($n = 26$) and Black participants ($n = 8$). Furthermore, six participants described themselves as mixed race, and two declined to answer. Finally, six participants described themselves as Hispanic/Latino. A total of nine participants were excluded due to poor performance on tasks ($n = 7$; see section "Spatial 2-back working memory task"), improper completion of the MA assessment ($n = 1$), or computer error during the task invalidating results ($n = 1$). Participants were recruited through the departmental participant pool system and were compensated with course credit for their participation. All procedures were approved by the University of Massachusetts Amherst Institutional Review Board (IRB).

Materials and procedure

MA, symbolic arithmetic, approximate arithmetic, and verbal and spatial working memory ability were measured with the tasks described below. Participants completed the two arithmetical tasks first, were given a 5-min break to prevent carryover effects, and then completed the two working memory tasks. The order of the tasks was counterbalanced within the arithmetic section and within the working memory section. Participants completed the mathematics anxiety assessment at the end of the study. A study visit lasted approximately 60 min. All the analyses were completed using Jamovi (The jamovi project, 2021) after completing data re-organisation in R (R Core Team, 2018; Wickham et al., 2018).

The Mathematics Anxiety Rating Scale: Brief Version (MARS-30 item)

To assess mathematics anxiety, the brief version of the Math Anxiety Rating Scale was administered (Suinn & Winston, 2003). This version is a 30-item scale adapted from the original 98-item scale. The items on the scale pertain to feelings of anxiety in academic and non-academic mathematical situations. It is a valid and reliable measure of mathematics anxiety. Some representative items include being given a pop quiz in a math class, figuring out your monthly budget, and receiving your final mathematics grade in the mail. Participants respond using a 5-point Likert-type scale; a response of 1 indicates low anxiety while a response of 5 indicates high anxiety. Participants' MA score was calculated by determining the sum of their responses. One participant left five questions blank, so their answers were reweighted according to their total responses.

Approximate arithmetic task

For the approximate arithmetic task, participants were instructed to estimate a quantity of dots after watching manipulations be performed (see Figure 1a). All dot arrays were set to have a numerosity ranging from 9 to 36. For all trials, an array of dots appeared on the computer screen to the right or left of an opaque occluder (square), and participants watched as the dot array moved behind the square. On half of the trials, another dot array appeared on the other side and also moved behind the square (simulating addition). On the remaining half of the trials, participants watched as some dots exited the square to the opposing side from where the first set entered (simulating subtraction). Participants were then presented with a third array below the square that they could use to input their response. The starting numerosity for this third array was randomly generated within a range of ± 2.5 times the true answer. They were instructed to adjust the quantity of dots in that array using keyboard keys (P to increase, L to decrease) to match as closely as possible their estimation of the number of dots behind the square. The quantity for this third array could never leave the boundary of ± 2.5 times the true answer. Participants had no time limit to input their answer. Participants were told to complete the problems as quickly and accurately as possible for two blocks with 45 trials each. They were also told by the experimenter that there was no "correct" answer because of how quickly the stimuli move, but they should do their best to match their answer as closely as possible. Note that while this is empirically inaccurate, we told this to participants to reduce feelings of frustration or anxiety related to evaluation and performance rather than the underlying representations. Practice problems were given prior to beginning the first block, and self-paced breaks occurred between blocks. To measure participant's performance on this task, we took the absolute value of the difference between the participant's answer and the true number of dots behind

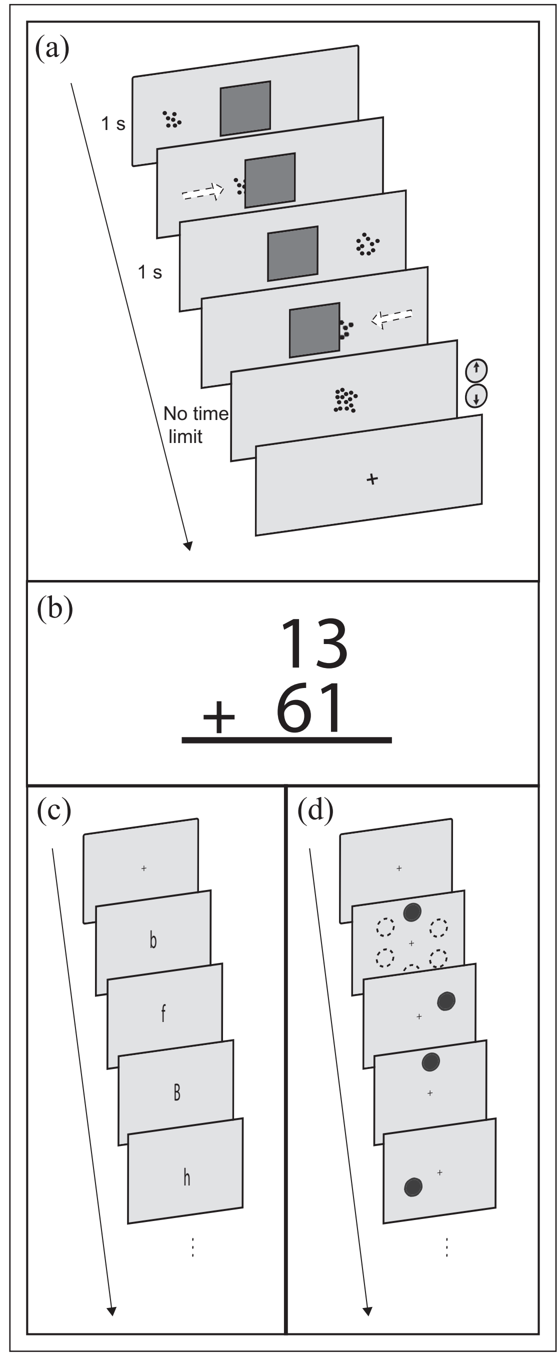

Figure 1. Diagram of methods.
(a) The dotted arrow represents the movement of the dots into the occluder. This pictured trial simulates addition, but half of the trials were subtraction trials where the dots left the occluder. (b) A single example symbolic arithmetic problem is presented. (c and d) The verbal and spatial 2-backs, respectively, are presented. These require a button press on each trial, with a 0.5 s presentation and a 2 s ISI. The dotted line circles in (d) represent the six possible locations (equidistant to the fixation cross in the centre).

Table 1. Descriptive statistics for all measures.

	Math anxiety score	Approx. arithmetic	Symbolic arithmetic	Verbal WM *d′*	Spatial WM *d′*
N	83	83	83	83	83
Missing	0	0	0	0	0
Mean	79.3	9.02	50.8	1.60	1.77
Median	79	8.50	47	1.55	1.66
Standard deviation	17.4	2.24	20.0	0.670	0.872
Minimum	41	4.50	14	0.157	0.0883
Maximum	132	15.8	123	3.83	4.13

WM: working memory.

the square in each trial. Because each participant's distribution of differences was skewed, the following analyses are performed with the median distance for each participant. One may wonder if participants verbalise the numerosities to transcode into a symbolic system to solve the task. Although we did not control for it in this experiment, Park and Brannon (2014) addressed this question by asking participants to solve approximate and symbolic arithmetic problems while engaging in articulatory suppression (continuously repeating a verbal syllable while solving the arithmetic problems). They found that articulatory suppression resulted in a decrement of performance only during symbolic arithmetic but not during approximate arithmetic, demonstrating that verbal transcoding in the approximate arithmetic task is highly unlikely (Park and Brannon, 2014).

Symbolic arithmetic task

In the symbolic arithmetic task, participants were presented with 2- and 3-digit addition and subtraction problems in one 7-min block. The problems were displayed one at a time on a computer screen using Arabic numerals and arranged in the vertical format (see Figure 1b). These problems were randomly pulled from a set of pre-generated problems that contained equal numbers of addition and subtraction (200 each) problems and equal amounts of carrying/borrowing per set. Participants responded using the number pad and were told to solve the problems as quickly and accurately as possible. Before the 7-min block began, participants were given practice problems to familiarise them with the use of the number pad and the requirements of the task. The total number of correct answers was calculated for each participant.

Verbal 2-back working memory task

For the verbal 2-back task, participants were presented with a stream of letters on the screen one at a time. The letters included "b," "f," "h," "m," "q," and "r" because they are phonologically distinct. Each letter could be presented in capitalised or lowercase form, which were considered to be the same letter for the purposes of answering. After each letter appeared, participants responded via a button press to indicate whether the letter matched the one displayed two trials prior (see Figure 1c). Each letter was presented for 0.5 s with an inter-trial interval of 2 s. Because there were no correct answers possible for the first two trials, they were discarded. After practice with feedback, participants completed four blocks of this task with 48 trials per block and self-paced breaks between blocks.

Spatial 2-back working memory task

For the spatial 2-back task, participants were presented with a series of white circles that appeared on the screen one at a time in any of six locations. These six locations were equidistant from a fixation cross in the centre of the screen. Participants responded with a button press after each circle appeared to indicate whether the location matched the location of the circle presented two trials prior (see Figure 1d). All parameters and procedures for this task were the same as those listed above for the verbal working memory tasks. For both working memory tasks, we calculated the participant's d', a measure of sensitivity. Participants ($n=6$) who had a negative d' on either task were excluded from the relevant subsequent analyses. One participant had a 100% hit rate in the spatial working memory task ($d'=\text{Inf}$). Their hit rate was substituted (hit rate = .999) to produce a sufficiently large d' value that could be used in subsequent analyses.

Results

Descriptives and correlations

Table 1 shows the descriptive statistics for all tasks (note that the approximate arithmetic measures are aggregates of participant's medians). Figure 2 shows zero-order correlations and scatterplots across all variables. MA was significantly negatively correlated with performance both on the symbolic arithmetic ($r=-.38$) and spatial 2-back ($r=-.25$) tasks. As expected, both 2-back tasks were positively

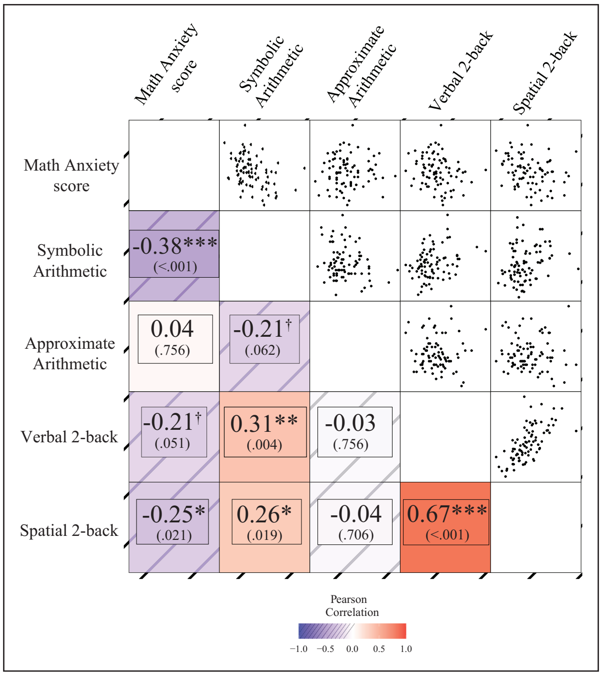

Figure 2. Correlation matrix and scatterplots for all analysed variables.

For the correlations, *p* values are presented in parentheses below the Pearson correlation value. For the scatterplots, the X-axis is represented by the column variable, and the Y-axis is represented by the row variable.

$^{***}p<.001$. $^{**}p<.01$. $^{*}p<.05$. $^{\dagger}p<.1$.

correlated with each other ($r=.67$), and symbolic arithmetic performance was correlated with performance on both the spatial ($r=.26$) and verbal ($r=.31$) tasks.

Approximate arithmetic analysis

Performance on approximate arithmetic was measured for each participant by finding the median of the distribution of absolute value distances between each given answer and the trial's true numerosity. If the hypothesis that those with high MA perform operations poorly is true, then we would expect those with high MA to have larger distances than those with low MA, on average. We ran two multiple regression models to predict MA scores from approximate arithmetic performance. First, we ran a model with only approximate arithmetic entered as a predictor, which was not significant, $R^2_{\text{Adjusted}}=.002$, beta $=0.304$, $t(82)=0.354$, $p=.724$. The second model included approximate arithmetic and both working memory measures as covariates (see Table 2). Although the working memory measures are highly collinear, they are included because they are not our regressors of interest and only serve to provide a clearer picture of the relationship between MA and performance. We failed to find evidence to support the above hypothesis, as there was no relationship between performance on approximate arithmetic and MA, beta $=0.218$, $t(82)=0.259$, $p=.796$.

Symbolic arithmetic analysis

For the symbolic arithmetic analysis, we followed the same procedure as above using symbolic arithmetic performance as the independent measure of interest instead of approximate arithmetic performance. As shown in Table 3, the relationship between symbolic arithmetic and MA was significant, even when accounting for each working memory difference, beta $=-0.294$, $t(82)=-3.141$, $p=.002$. When entered as a hierarchical regression, including both working memory measures leads to a non-significant model, $R^2=.0679$, $F(2,80)=2.91$, $p=.06$, with spatial working memory (WM), beta $=-3.94$, $t(82)=-1.365$, $p=.176$, and verbal WM, beta $=-2.16$, $t(82)=-0.575$, $p=.567$, failing to significantly predict MA. Adding symbolic arithmetic in a second model significantly improves the change in R^2, $\Delta R^2=0.104$, $F(1,79)=9.87$, $p=.002$, suggesting that performance on symbolic arithmetic relates to MA above and beyond the effects of WM.

Post hoc Bayesian analysis

To measure the strength of evidence in favour of the null hypothesis, we ran a Bayesian correlation between approximate arithmetic performance and MA. We did not include WM performance in this analysis because accounting for individual differences in WM did not appear to change the (lack of) relationship between approximate arithmetic performance and MA (see Table 2). We used the default settings on jsq package—the Jamovi adaptation of JASP (JASP Team, 2020)—to calculate Bayes factors based on Pearson's rho (Ly et al., 2016, 2018). The resulting correlation showed moderate evidence for the null hypothesis ($r=.0393$, $BF_{01}=6.86$).

Analysis of categorical MA

Although we treated MA as a continuous variable, it is more common to form groups from extreme scores and treat MA as a categorical variable (e.g., Colomé & Núñez-Peña, 2021; Suárez-Pellicioni et al., 2014). To keep consistent with the literature, we divided all participants into tertiles based on their MA score to run a one-way analysis of variance (ANOVA) for approximate arithmetic performance. The low MA group had MA scores ranging from 35 to 72 ($M=59.8$). The medium MA group scored between 72 and 86 ($M=79.2$) and the high MA group scored higher than 86 ($M=96.2$). The ANOVA revealed no difference across any of the groups ($F=0.441$, $p=.645$, $\eta^2=.011$). No follow-up contrasts were run. Our results from the regression and ANOVA analyses suggest that the use of MA as a continuous variable produces results consistent with the creation of categorical MA groups.

Discussion

We hypothesised that if MA compromises performance specifically related to precise, symbolic processing, then

Table 2. Regression analysis for approximate arithmetic predicting math anxiety score.

Predictor	Estimate	*SE*	95% confidence interval		*t*	*p*
			Lower	Upper		
Intercept	87.737	9.247	69.33	106.14	9.489	<.001
Approx. arithmetic	0.218	0.842	−1.46	1.89	0.259	.796
Verbal WM *d′*	−2.148	3.774	−9.66	5.36	−0.569	.571
Spatial WM *d′*	−3.917	2.901	−9.69	1.86	−1.350	.181

SE: standard error; WM: working memory.
Adjusted $R^2 = .0687$.

Table 3. Regression analysis for symbolic arithmetic predicting math anxiety score.

Predictor	Estimate	*SE*	95% confidence interval		*t*	*p*
			Lower	Upper		
Intercept	100.1048	5.7495	88.661	111.549	17.4110	<.001
Symbolic arithmetic	−0.2940	0.0936	−0.480	−0.108	−3.1414	.002
Verbal WM *d′*	0.0436	3.6283	−7.178	7.265	0.0120	.990
Spatial WM *d′*	−3.3226	2.7421	−8.781	2.135	−1.2117	.229

SE: standard error; WM: working memory.
Adjusted $R^2 = .171$.

only symbolic arithmetic, and not approximate arithmetic, would predict MA status. On the contrary, if performing operations involving numeric quantities is a cognitive primitive that is disrupted or less developed among people with MA, performance in both our approximate arithmetic and symbolic arithmetic tasks would predict MA status. We found support for the former hypothesis in that symbolic arithmetic, but not approximate arithmetic, was related to MA. This held true even after accounting for the two different types of working memory. When entered into a regression alone, the working memory tasks together accounted for 6.8% of the variance in MA.

The lack of a relationship between approximate arithmetic performance and MA suggests that MA deficits are related specifically to symbolic processing and not to using perceptually based operations to manipulate numerosities. We found a relationship between symbolic arithmetic and MA that is consistent and comparable with previous literature on the topic (Barroso et al., 2020; Hembree, 1990; Ma, 1999). However, the novel aspect of our study, which disentangles performing operations without the use of symbolic stimuli, indicates that primitive operational processes are unimpaired in people with high MA. Previous work suggests that nonverbal quantity manipulation as in approximate arithmetic may be an important factor that links primitive quantitative abilities to symbolic arithmetic, although there is counterevidence (Hyde et al., 2014; Khanum et al., 2016; Park & Brannon, 2013, 2014; J. Wang et al., 2016, 2017, 2021); however, see also Bugden et al. (2021), Sasanguie et al. (2014), Szkudlarek and Brannon (2017), and Szkudlarek et al. (2021). Furthermore, our study involved the *production* of a computed answer, rather than a binary decision between correct and incorrect options. Because of this, we expected similar patterns in performance by those with high and low MA in both symbolic and non-symbolic tasks. If operational processes without symbolic stimuli were found to be impaired in those with MA, then there would be potential for targeted interventions in childhood that could reduce early negative math experiences that lead to increased MA (Maloney, 2016). However, much like the work showing that ANS acuity is not impaired in those with MA (Colomé, 2019; Dietrich et al., 2015; Hart et al., 2016, 2017; Lee & Cho, 2018; Z. Wang et al., 2015), we found these operational processes were similarly unimpaired in those with MA.

Our results largely align with the hypothesis that precise or symbolic representation is necessary to elicit performance deficits in those with MA. The relationship between MA and symbolic arithmetic holds while accounting for verbal and spatial working memory, despite approximate arithmetic failing to relate to MA entirely, which strengthens this hypothesis.

Our other finding relating spatial—and to a lesser extent, verbal—working memory to MA is consistent with early explanations of MA disrupting working memory resources (Ashcraft & Faust, 1994; Hopko et al., 1998). Furthermore, spatial working memory has continued to be a topic of interest in MA and could still constitute a reduced capacity under the causal model.

Previous work has shown connections between spatial processing and MA. Namely, people with high MA often have difficulty with mental rotation tasks, such as matching 3D objects or determining whether two objects are mirrored (Ferguson et al., 2015; Núñez-Peña et al., 2019; Sokolowski et al., 2019). Measures of visuospatial working memory also correlate with MA (Ashkenazi & Danan, 2017; Soltanlou et al., 2019). Our results showing a significant correlation between MA and spatial 2-back working memory performance are consistent with these previous findings.

That said, the approximate arithmetic task requires the maintenance of information in spatial working memory. To solve the task, the participant must represent the array on the visuospatial sketchpad (Baddeley, 1992) and either update by integrating a new array or removing a separate array. Therefore, if people with high MA do have impaired spatial working memory, then it is not immediately clear why they did not perform worse on the approximate arithmetic task based on that factor alone.

The inconsistency between findings on spatial working memory and approximate arithmetic can be explained by cognitive demands in each task. One possible reason concerns the spatial working memory task demands. The dots to be held in memory in the 2-back task were only shown for 0.5 s, with an inter-trial interval of 2 s. This meant that participants had to make a response within 2 s, which could have been challenging for those with spatial processing difficulties to sustain across all 48 trials. In contrast, responses in the approximate arithmetic task were entirely self-paced. Thus, it may be that the challenges of the spatial 2-back underlie the relationship between spatial working memory and MA, rather than general spatial processing skills.

Another possibility is that the type of cognitive demands in a 2-back spatial task is qualitatively different from the demands in the approximate arithmetic task. In the 2-back task, items in memory slots need to be constantly updated to perform well. In the approximate arithmetic task, however, a constant update is not necessary and a manipulation in the visuospatial sketch pad is sufficient to perform the task well. Therefore, the 2-back task may not have been the best task that taps into critical spatial processes needed in approximate arithmetic.

In addition, our results could also be explained by fear of evaluation rather than cognitive factors. In a study of pre-service elementary school teachers, a majority expressed that the emphasis on correct answers in math courses caused their MA (Harper & Daane, 1998). It is possible that those teachers do not have a full understanding what caused their first experiences MA. However, because our participants were also adults, they may have responded differently to approximate arithmetic because of the evaluation component. It is clear that symbolic arithmetic has a correct answer, and people asked to solve arithmetic problems need no clarification on the instructions. The approximate arithmetic task, however, used numerosities that moved far too quickly for precise enumeration to occur. Thus, it is near impossible for participants to consistently produce the exact quantity of hidden dots. Furthermore, participants were instructed to produce the quantity "as close as possible" to the hidden dots, further de-emphasising that they could find the correct answer. We may have shown different results had we directly instructed the participant to find the correct answer, if this evaluation hypothesis is true.

Taken all together, our results highlight a potential avenue for further study regarding spatial processing in MA and provide further evidence that basic ANS functions are unimpaired in adults with MA. Those with high MA did not perform worse on an approximate arithmetic task using dot arrays, despite performing poorly on a symbolic arithmetic task. This suggests that the ability to perform basic numerical operations is not hindered or reduced in adults with MA, but that abilities related to manipulating symbolic quantities are affected. Our results, alongside the many mixed findings relating ANS function to MA in adults and children, suggest that the reduced cognitive capacities model's causal factor of "basic number skills" should not include numerosity processing. However, we suggest that there may be an exception for incongruence between numerosity and other spatial magnitudes in non-symbolic arrays. Further work may also focus on spatial abilities that may be impaired and further elucidating the mechanism by which precise, symbolic representation interferes with performance in those with MA.

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