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Full title: Teasing apart the unique contributions of cognitive and affective predictors of math performance

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Abstract

Math permeates everyday life and math skills are linked to general educational attainment, income, career choice, likelihood of full-time employment, and health and financial decision-making. Thus, researchers have attempted to understand factors predicting math performance to identify ways of supporting math development. Work examining individual differences in math performance typically focuses on either cognitive predictors, including inhibitory control and the Approximate Number System (ANS; a non-symbolic numerical comparison system), or affective predictors, like math anxiety. Studies with children suggest these factors are interrelated, warranting examination of whether and how each uniquely and independently contributes to math performance in adulthood. Here, we examined how inhibitory control, the ANS, and math anxiety predicted college students' math performance (N=122, mean age=19.70 years). Using structural equation modelling, we find that although inhibitory control and the ANS were closely related to each other, they did not predict math performance above and beyond effects of the other while also controlling for math anxiety. Instead, math anxiety was the only unique predictor of math performance. These findings contradict previous results in children and reinforce the need to consider affective factors in our discussions and interventions for supporting math performance in college students.

Introduction

Math skills are used every day for tasks such as calculating a tip at a restaurant or choosing which check-out line at the grocery store is the shortest. Although we may often think of math abilities as purely academic skills, an abundance of studies indicates that children's and adults' math skills are associated with a wide range of important outcomes. Variability in math performance is associated with educational attainment, income, career choice, likelihood of full-time employment, and health and financial decision-making (see [1-4]). Given the wide-ranging impacts of math skills on everyday life, decades of research have attempted to identify predictors of individual differences in math abilities. Past work has been somewhat siloed, often heavily focusing on child populations, with a large body of research examining cognitive predictors that are consistently related to math performance, including domain-general cognitive abilities such as inhibitory control and domain-specific cognitive abilities such as the functioning of the Approximate Number System, or ANS (e.g., [5, 6]). Separately, other studies examining dispositional characteristics find that affective factors such as math anxiety also robustly predict math achievement (e.g., [7]). Although these factors have typically been examined in relative isolation, recent work suggests there may be interrelations between them ([8]; [9]; [10]; [11]), primarily in studies of children, leading to questions about the unique contributions of cognitive and affective predictors of math performance in adulthood.

Cognitive Predictors of Math Performance

Math performance is closely related to many cognitive skills, including both domain-general and domain-specific abilities (see [12]). Here, we examine two cognitive predictors of math performance that have been widely studied: inhibitory control and the Approximate Number System.

Inhibitory control.

Individuals' inhibitory control, or the ability to ignore distractions and inhibit a prepotent response, has been found to be associated with math achievement throughout the lifespan with moderate effect sizes [5]. Inhibitory control is hypothesized to be one of three distinct yet related components of executive functioning, along with set shifting and information monitoring (see [13]). Although many aspects of executive functioning may support math learning and problem solving, evidence suggests that inhibitory control is particularly strongly related to math achievement, at least in childhood (e.g., [14]). Individuals with higher inhibitory control tend to perform better in math than those with worse inhibition, even when controlling for other general cognitive abilities and demographic factors, as well as other executive functioning skills [14, 15].

Throughout development, inhibition has been linked to a variety of math skills [16, 17]. Preschool-aged children's inhibitory control is related to foundational math abilities, including approximation of quantities [8-10], as well as counting, simple non-verbal arithmetic, and number recognition [18-20]. Additionally, inhibitory control is associated with performance in school-based math skills, including arithmetic, number sequencing, and graphical representation of data [9, 18]. Furthermore, inhibition may be particularly important for problem solving, strategy choice, and efficient allocation of cognitive resources [17].

The majority of this past work examining associations between inhibitory control and math achievement has been conducted with children, and inhibition may be particularly important for math learning. However, a few studies have explored the role of inhibitory control in math problem solving for adolescents and adults and generally find that specific math skills may also depend on adults' inhibitory control. For example, comparing fractions with common numerators (such that the larger fraction is the one with the smaller denominator) or comparing decimals have been linked to adults' inhibitory control [21, 22]. Moreover, inhibitory control may be implicated in adults' advanced math problem solving, which often conflicts with existing knowledge, as individuals must override prior knowledge to solve new problems (i.e., comparing fractions, in which simply comparing the individual numerator and denominator values may lead to incorrect responses, or mapping number symbols onto a novel, nonstandard number line; [23]).

Approximate Number System. In addition to domain-general skills like inhibition, domain-specific abilities like numerical comparison are also closely related to math performance. One such numerical system that has been the subject of ample investigation is the Approximate Number System (ANS), which allows for representation of large quantities without the use of formal symbols [24, 25]. The ANS is present from birth and provides imprecise representations of quantities larger than 4 that allow for comparison and approximate arithmetic. Discrimination of sets using the ANS is ratio-dependent, such that performance is more accurate for sets with a larger relative difference (larger ratio) than for sets with a smaller relative difference (smaller ratio). Individual differences in the ANS exist, such that individuals vary in the acuity of their ANS representations: While some adults may be able to reliably discriminate between sets that differ by a 9:10-ratio, other adults may only be able to discriminate between sets that differ by a 6:7-ratio [26]. These individual differences in the ANS are related to variability in symbolic math skills from early childhood through adulthood, such that individuals with more precise ANS representations tend to perform better on a broad range of math assessments with most work reporting moderate effect sizes [6, 27-32].

Under some theoretical accounts, the ANS is hypothesized to support formal math performance by mapping its non-symbolic representations with symbolic number representations

[30, 31, 33-39]. Alternatively, some researchers posit that the ANS may serve as an "error detection" mechanism that provides a sense of certainty about number-related judgements, providing rough estimates of computations and aiding in detection of miscalculations [40-42]. Still other researchers argue that the ANS may be linked to symbolic math performance via affective factors, including motivation. Specifically, it is possible that better ANS acuity may increase attention to or engagement with numerical and math-related information (e.g., [43]) or may lead to more confidence in math [44].

Importantly, the ANS is argued to be causally related to symbolic math performance, as training studies with children and adults have found that improvements in ANS acuity are associated with subsequent improvements in symbolic math performance [38, 44-48]. However, other researchers have recently shared concerns about the methods and measures in these training studies, calling for further investigation of the link between the ANS and symbolic math performance [49-51] (but see [52, 53]).

Affective Predictors of Math Performance

In addition to the aforementioned cognitive factors that are associated with math performance, individuals' attitudes and feelings toward math can also influence their performance. Specifically, math anxiety, or the feeling of apprehension and discomfort when using numbers or solving math problems, is closely tied to math performance from childhood through adulthood [7, 54-60]. Individuals with higher math anxiety tend to perform worse in math than those with lower levels of math anxiety, typically with moderate effect sizes. These associations are cross-national, as higher math anxiety is associated with lower math performance in nearly every country studied [61].

Multiple theories explaining the link between math anxiety and math performance have been put forward. The “Debilitating Anxiety” Model theorizes that having math anxiety interferes with the ability to successfully perform in math, such that math anxiety precedes and results in poor math performance (e.g., [56, 57, 62-67]). On the other hand, the “Deficit” Model theorizes that a history of poor math performance leads to the development of math anxiety and associated negativity toward math, such that math anxiety instead stems from poor math performance (e.g., [68-72]). A further hypothesis is the “Reciprocal” Model, which claims that there is a bidirectional relation between math anxiety and math performance, suggesting that both of these processes may be at play (e.g., [73-76]).

Interrelations Between Cognitive and Affective Predictors of Math Performance

Inhibitory control and ANS. Recent evidence suggests that cognitive predictors of math performance may be closely related to one another, at least in developmental studies. For example, over the past decade researchers have examined the relations between the ANS and inhibitory control, attempting to parse out their unique relations with math performance. This work finds that ANS performance and inhibitory control are often correlated (e.g., [8, 9, 77]). Furthermore, some researchers have argued that links between the ANS and math performance may be explained by inhibitory control in preschool and elementary school-aged children (e.g., [8, 9]), whereas others find that although these cognitive abilities are related to one another, they remain unique predictors of math performance among similarly aged children (e.g., [10, 78]).

To date, the interplay of these cognitive factors in predicting adult math performance has been understudied. The only study to examine the role of inhibitory control for the association between ANS and math abilities in adults is a recent study from our own group [11]. Using a subset of the data used in the present study, we found that performance on a non-symbolic number comparison task that used stimuli created using Panamath (www.panamath.org) was significantly related to applied word problem solving and calculation, even when controlling for inhibitory control as measured by performance on a Stroop task and a Go/No-Go task. In contrast, inhibitory control was significantly predictive of only arithmetic fluency skills and not calculation or problem-solving.

Inhibitory control and math anxiety. More recently, researchers have begun to bridge the gap between the two bodies of literature examining cognitive and affective predictors of math and explore how the two may relate to one another. For instance, a few recent studies have examined the links between math anxiety and inhibitory control in adults, finding that higher math anxiety is typically associated with lower inhibitory control [79-81]. A similar pattern of findings has been documented with children as well, but fewer studies have investigated these trends [82] (but see [83]). These findings are in line with the Deficient Inhibition Mechanism theory of math anxiety [84] and Attentional Control Theory [85], which suggest that high levels of math anxiety may lead individuals to devote increased mental resources to worry-related thoughts rather than math problem solving. In other words, math anxiety may be related to math performance because individuals with higher levels of math anxiety are unable to inhibit their worries.

ANS and math anxiety. A few studies have investigated the links between the ANS and math anxiety. Some work finds that these constructs are correlated among young adults [86-88], in line with a Deficit Model view of math anxiety where poorer foundational math skills (in this case, numerical comparison) may lead to increased math anxiety. On the other hand, others find that ANS performance and math anxiety are unrelated in adulthood [89] as well as early childhood [90], leaving open the question of how these factors may overlap or exert independent effects on math performance. Despite the relevance of both the ANS and math anxiety demonstrated in past research, relatively few studies have examined how these factors operate in concert with one another.

The Current Study

The evidence reviewed above suggests that inhibitory control, the ANS, and math anxiety are not only related to math performance, but likely also have interrelations between them. However, no work to date has examined both cognitive and affective factors together to tease apart the unique contributions of each on math performance, particularly in adulthood as opposed to childhood when math skills are still being acquired. Given recent evidence that these predictors may be interrelated (e.g., [8, 81, 87]), and the relevance of math skills throughout the lifespan for daily activities from budgeting finances to following recipes, we ask whether young adults' ANS performance, inhibitory control, and math anxiety remain independent predictors of math performance when accounting for the other factors. To this end, participants completed multiple measures of ANS performance and inhibition, a measure of math anxiety, as well as multiple measures of math performance. Given the multiple assessments of math used here, we also explore whether these cognitive and affective factors relate similarly or differently to the individual math outcomes.

Method

Participants

In total, 141 students from KU Leuven in Belgium (M_{age} = 20.23 years; *SD* = 2.05; range = 17.89-29.40 years) took part in return for course credits or a small monetary compensation. All adult participants provided written informed consent before participation. Participants were excluded from all analyses if any of their scores on one of the assessments was 3*SD* below or above the sample mean for that assessment (*n* = 19). The resulting sample consisted of 122 adults (M_{age} = 19.70 years; *SD* = 2.05). This study was approved by the Ethical Committee of the KU Leuven (G-2016 12 703).

Procedure

All assessments were completed during a single laboratory visit. All participants first completed the paper-and-pencil math tests (first Arithmetic Fluency, then Arithmetic Skills; see below). Next, participants completed the non-symbolic number comparison tasks assessing the ANS. Both numerosity comparison tasks were administered in a counterbalanced order (half of the participants started with the Panamath task, the other half with the Gebuis & Reynvoet "G&R" task). Then, four inhibition tasks were administered of which the order was counterbalanced according to a Latin-square design. However, preliminary confirmatory factor analysis indicated that two of the inhibition tasks did not load well onto the inhibition factor (an animal and number Stroop task, described in more detail here [78]), perhaps due to differences in the underlying aspect of inhibition addressed (see [91]). As such we did not include those two tasks in our analyses, and we describe only the included inhibition tasks below. Finally, participants completed the paper-and-pencil math anxiety questionnaire at the end of the visit to ensure that having participants reflect on their math anxiety did not elicit anxiety and influence later math performance. Numerosity comparison and inhibition tasks were computerized and presented on a 15.4-inch laptop. In total, testing lasted about one hour.

Measures

Math tests. Participants completed two math tests: Arithmetic Fluency and Arithmetic Skills (which included subtests assessing Procedural Calculation, Mental Representations and Word Problems), always in that order. Scores from each assessment (Arithmetic Fluency, Procedural Calculation, Mental Representations and Word Problems) were z-scored prior to all analyses.

Arithmetic Fluency. To measure arithmetic fluency, the ‘Tempo Test Arithmetic’ was used (‘*Tempo Test Rekenen*’, [92]). This test is comprised of five separate columns: addition, subtraction, multiplication, division, and mixed operations with 40 items of increasing complexity in each column (e.g., 1 x 4 as first item of multiplication, 5 x 17 as last item). As this test was developed for elementary school children, we reduced the time limit to 30 seconds per column instead of one minute. Participants were instructed to answer as many items correctly as possible. One point was given for each correct item. This assessment has demonstrated adequate psychometric validity and reliability with adults ([81, 93]). The number of correctly solved problems across all five columns was used as a measure of arithmetic fluency. In total, participants were presented with 200 items and averaged 104.86 correct responses (*SD* = 17.45) in the time allowed.

Arithmetic Skills. Four subtests of the ‘Cognitive Skills Arithmetic, 5th grade’ test (‘*Cognitieve Deelvaardigheden Rekenen – 5e graad*’, [94]) were used to measure participants’ procedural calculation skills and abilities to solve applied word problems. Participants were given 15 minutes to complete the 20 items across the four subtests. The number of correctly solved problems was used as a measure of each domain of arithmetic skill. This assessment has demonstrated adequate internal consistency with adults for the overall assessment with all nine subtests (α = .75; [81, 94]). Although this assessment is appropriate for individuals through secondary school and higher education and can be used to calculate normed scores for adult populations, standardized scores are only available for the entire test (i.e., all nine subtests). As such, we analyze raw scores, which could range from 0 to 5, on each subtest. The measure of ***procedural calculation*** was drawn from the Procedural Calculation subtest, which consisted of five items which required participants to complete multi-step operations (e.g., 1263 + 861 + 73 + 445 = ?). On average, participants correctly completed 2.94 items (*SD* = 1.07). The measure of ***mental representations*** was drawn from the *Mathematical Reasoning* subtest, which consisted of five items which required participants to interpret and solve a procedural computation (e.g., “370.5 is 0.9 less than …”; *M* = 3.75, *SD* = 1.15). The measure of ***applied word problems*** was drawn from two other subtests; the *Word Problems Without Distraction* contained 5 items with only item-relevant information (e.g., “Emily has 40 marbles. She gives away 2 marbles. How many marbles does she have left?”), and the *Word Problems with Distraction* contained 5 items with additional item-irrelevant information (e.g., “Lisa has 2 marbles and 3 stickers. She gets 40 marbles. How many marbles does she have now?”). Given the similarities in the underlying dimensions of math measured by these two subtests, scores on these tasks were combined. Of the 10 items, participants correctly completed 5.89 on average (*SD* = 1.91).

Inhibitory control tasks. To measure participants’ inhibitory control, they completed two computer-based Go/No-Go tasks in which one task used numerically relevant stimuli and the other used numerically irrelevant stimuli. Participants were instructed to respond as quickly as possible to all stimuli except for a specified stimulus, thus requiring them to develop and subsequently inhibit a prepotent response. The task consisted of 10 practice trials followed by

100 test trials, in which the “Go” stimulus was presented for 75% of trials and the “No-Go” stimulus was presented for the remaining 25%. A fixation cross was presented for 500 ms, the stimulus was presented for 90 ms, and participants had 750 ms to respond before the start of the next trial. In the *Number Go/No-Go task*, the “Go” cue was the Arabic numeral “1”, while the “No-Go” cue was the Arabic numeral “6”. In the *Animal Go/No-Go task*, the “Go” cue was a picture of a horse, while the “No-Go” cue was a picture of a bird. The number of commission errors (i.e., a response was given despite the No-Go stimulus) in each task was used a measure of inhibition difficulty.

Numerosity comparison (ANS) tasks. Participants completed two numerosity comparison tasks assessing ANS performance for which stimuli were generated with different software (Panamath and G&R). Both tasks started with 6 practice trials with auditory feedback, and a test phase of 144 trials administered in a single block. Each trial began with the presentation of a fixation cross on an otherwise blank screen, after which dot arrays (yellow and blue dots) were simultaneously presented on the left and right sides of the screen for 500 ms. Participants were instructed to indicate which side contained more dots by pressing the ‘f’ key (left hand) or the ‘j’ key (right hand). Half of the trials featured the correct answer on the left side of the screen, the other half on the right. Numerosities ranged from 10 to 40 and six ratios were used: 1.11, 1.14, 1.2, 1.25, 1.5 and 2. The two tasks were completed sequentially, and the order was counterbalanced across participants. Accuracy scores were used for all analyses (see also [95]).

Panamath. One numerosity comparison task was created and administered using the Panamath Software (downloaded from the Panamath website; www.panamath.org; [96]). The version used here contained three trial types: *area-congruent* trials (i.e., trials in which the dot array that contained more dots had the larger cumulative surface area), *area-neutral* trials (i.e., trials in which both dot arrays had the same cumulative surface area), and *area-incongruent* trials (i.e., trials in which the dot array that contained more dots had the smaller cumulative surface area. Note that in this case, the cumulative perimeter between the dot arrays was equated).

Gebuis & Reynvoet (G&R). The other numerosity comparison task was an adapted version of the one used by Gebuis and Reynvoet [97] and was administered using E-prime 3.0. In this task, five visual cues were controlled for across trials: convex hull (i.e., the area subtended by each dot array), total surface area (i.e., the aggregate surface area of all dots in one array), dot item size (i.e., the average diameter of the dots presented in one array), total circumference (i.e., the aggregate circumference of all dots in one array), and density (i.e., surface area divided by convex hull). This task contained two trial types: fully congruent and fully incongruent, meaning that all the visual cues were congruent during congruent trials and incongruent during incongruent trials.

Math anxiety. Math anxiety was assessed using the Abbreviated Math Anxiety Scale (AMAS; [98]) translated to Dutch. This scale has been used cross-culturally and shows good psychometric properties in child and adult populations (see [99] for a discussion of the usefulness of the AMAS). Notably, this scale has been used in Dutch in a similar sample with university students in Belgium previously ([100]). The questionnaire includes nine items, each rated on a 5-point Likert scale. Participants' math anxiety scores were calculated as the sum of their responses to all nine items. For this sample, internal consistency measured using Cronbach's α for the total score was 0.86.

Analysis Plan

We aimed to investigate whether ANS performance, inhibitory control, and math anxiety uniquely relate to math performance, even above and beyond the influences of the other variables. To do so, we first estimated a measurement model, then combined the latent variables into a structural model to estimate math performance.

A measurement model was first employed to confirm that the hypothesized latent variables of math performance, ANS performance, inhibitory control, and math anxiety indeed were a good fit for the data. We assigned arithmetic fluency, procedural calculation, mental representation, and word problems performance to a latent variable factor for math performance. Performance on the two ANS tasks using Panamath and G&R stimuli were assigned to a latent variable factor for ANS performance. Performance on the Numerical Go/No-Go task and the Non-Numerical Go/No-Go task were assigned to a latent variable factor for inhibitory control (note that these tasks measured commission errors, and so this factor describes inhibitory control problems). Finally, participants' math anxiety was created as a single indicator latent variable from their scores on the AMAS (no difference in the pattern and significance of results was observed when math anxiety was modeled as a latent variable with items from the AMAS serving as indicators). No residual variance terms were added, and associations between latent factors were freely estimated.

Using the identified factor structure, a structural model was then estimated to compare the relative strength of the paths from ANS performance, inhibitory control, and math anxiety to math performance. Specifically, directional pathways from each of these theoretical predictors to math performance were estimated, and predictors were allowed to covary with one another. Additional exploratory analyses predicting each individual math outcome were then estimated to compare the relative strength of the paths from ANS performance, inhibitory control, and math anxiety to each math outcome separately (i.e., in each model, math performance was estimated as a single indicator latent variable using scores from one math subtest). As in the main structural model, directional pathways from each theoretical predictor to the measure of math performance were estimated and predictors were allowed to covary with one another.

All analyses were performed using the *lavaan* package in R [101], and model fit was evaluated based on conventional fit indices (i.e., non-significant chi-square, RMSEA < .06, CFI/TLI > .95, and SRMR < .08; [102]).

Results

Descriptive statistics and bivariate correlations for study variables are presented in Table 1. As participants' age was uncorrelated with all other study variables, we did not include age as a covariate in further analyses.

Measurement Model

The confirmatory factor analyses estimated in the measurement model confirmed that the model fit the data well, with $\chi^2(22) = 17.50$, $p = .735$, CFI = 1.000, TLI = 1.060, RMSEA = 0.000, 90% CI [0.000, 0.056], and SRMR = 0.048. Arithmetic fluency, procedural calculations, mental representations, and word problems performance all loaded significantly onto the math performance factor (all *p*s < .01). Panamath and G&R performance both loaded significantly onto the ANS factor (all *p*s < .05). Numerical Go/No-Go and Non-Numerical Go/No-Go performance both loaded significantly onto the inhibitory control factor (all *p*s < .01).

The covariance between math performance and math anxiety was statistically significant ($p = .007$), but covariances between math performance and ANS performance and between math performance and inhibitory control were not significant (all *p*s > .370). Meanwhile, the covariance between ANS performance and inhibitory control was statistically significant (*p* = .020), but covariances between ANS performance and math anxiety, as well as between inhibitory control and math anxiety, were not statistically significant (all *p*s > .130). The results from the measurement model are displayed in Figure 1.

Structural Model

Given these results from the measurement model, the structural model was estimated using the factor structure shown in Figure 2. The model fit the data well, $\chi^2(22) = 17.50$, $p = .735$, CFI = 1.000, TLI = 1.060, RMSEA = 0.000, 90% CI [0.000, 0.056], and SRMR = 0.044. There was a significant covariance between ANS and inhibitory control ($p = .020$). Critically, however, the paths from ANS to math performance, and from inhibitory control to math performance, were not statistically significant, $\beta = .04$, $p = .834$, and $\beta = -.07$, $p = .657$, respectively. The only significant predictor of math performance was math anxiety, $\beta = -.32$, $p = .008$. This pattern of results, where math anxiety is the only significant predictor of math performance, is consistent when only ANS or only inhibitory control is included as the sole cognitive factor in the model.

Exploratory Analyses Predicting Each Math Outcome Independently

To explore whether the patterns of associations reported above differed for different subdomains of math (i.e., arithmetic fluency, procedural calculations, mental representations, and word problem solving), identical structural models were estimated using the factor structure shown in Figure 2 predicting each math outcome separately. We first predicted performance in the *arithmetic fluency* subtest. Results from this model are presented in Figure 3. This model fit the data well, $\chi^2(5) = 1.62$, $p = .899$, CFI = 1.000, TLI = 1.134, RMSEA = 0.000, 90% CI [0.000, 0.054], and SRMR = 0.014. There was a significant covariance between ANS and inhibitory control ($p = .016$). As in the main structural model, the paths from ANS to arithmetic fluency performance, and from inhibitory control to arithmetic fluency performance, were not statistically significant, $\beta = -.21$, $p = .239$, and $\beta = -.14$, $p = .325$, respectively. The only significant predictor of arithmetic fluency performance was math anxiety, $\beta = -.21$, $p = .028$.

We next predicted performance in the *procedural calculation* subtest. Results from this model are presented in Figure 4. This model fit the data well, $\chi^2(5) = 1.94$, $p = .858$, CFI = 1.000, TLI = 1.114, RMSEA = 0.000, 90% CI [0.000, 0.068], and SRMR = 0.019. There was a significant covariance between ANS and inhibitory control ($p = .023$). As in the main structural model, the paths from ANS to procedural calculation performance, and from inhibitory control to procedural calculation performance, were not statistically significant, $\beta = .12$, $p = .461$, and $\beta = -.05$, $p = .699$, respectively. The only significant predictor of procedural calculation performance was math anxiety, $\beta = -.23$, $p = .013$.

We then predicted performance in the *mental representations* subtest. Results from this model are presented in Figure 5. This model fit the data well, $\chi^2(5) = 0.63$, $p = .987$, CFI = 1.000, TLI = 1.176, RMSEA = 0.000, 90% CI [0.000, 0.000], and SRMR = 0.010. There was a significant covariance between ANS and inhibitory control ($p = .023$). As in the main structural model, the paths from ANS to mental representations performance, and from inhibitory control to mental representations performance, were not statistically significant, $\beta = .12$, $p = .462$, and $\beta = .02$, $p = .897$, respectively. Math anxiety was only marginally significantly related to mental representations performance, $\beta = -.17$, $p = .077$.

Finally, we predicted performance in the *word problems* subtest. Results from this model are presented in Figure 6. This model fit the data well, $\chi^2(5) = 0.94$, $p = .936$, CFI = 1.000, TLI =

1.148, RMSEA = 0.000, 90% CI [0.000, 0.032], and SRMR = 0.014. There was a significant covariance between ANS and inhibitory control (p = .024). The paths from inhibitory control to word problem solving performance, and from math anxiety to word problem solving performance, were not statistically significant, β = .11, p = .426, and β = -.06, p = .551, respectively. ANS performance was marginally significantly related to word problem solving performance, β = .30, p = .098.

Discussion

Past work examining factors that predict math performance has typically focused on either cognitive predictors, including inhibitory control and numerical comparison abilities, or affective predictors, like math anxiety, that influence individuals' math performance while also heavily focusing on children. In this study, we bridged these two bodies of literature and examined the associations between cognitive and affective predictors of math performance in adults. Using structural equation modelling, we find that although inhibitory control and the ANS are closely related to each other, they did not predict math performance above and beyond the effects of the other and math anxiety. Instead, math anxiety was the only unique predictor of math performance in this sample of college-aged adults. Furthermore, we find that these associations may differ based on the type of math performance measured, as these effects were consistent in predicting arithmetic fluency, procedural calculations, and mental representations performance, but not word problem solving.

The Unique Role of Math Anxiety in Math Performance

Above and beyond the effects of the cognitive predictors, math anxiety remained significantly associated with adults' math performance. Participants who reported greater math anxiety tended to perform significantly worse in math than those who reported less math anxiety. This finding is consistent with prior work finding that math anxiety is often closely related to math performance across the lifespan (see [7, 56], for reviews). As noted in the introduction, links between math anxiety and math performance have been the target of multiple possible theories, including the Debilitating Anxiety Model (e.g., [56, 57, 62-67]), the Deficit Model (e.g., [68-72]), and the Reciprocal Model (e.g., [74, 75, 103]). Although our cross-sectional findings are consistent with these theoretical explanations, they do not allow us to compare these competing hypotheses directly. Instead, longitudinal and experimental work is needed to identify the causal directions of these associations and tease apart these processes more carefully.

Nonetheless, our findings tentatively suggest that the development of interventions aimed at reducing math anxiety might provide useful targets for encouraging better math performance in college students. Such intervention studies would also help to test the potential causal relations and inform the theoretical debate regarding the association between math anxiety and math performance. Recent studies have investigated how training the ANS and inhibitory control may impact math performance in both adults and children (see [38, 44, 45, 48, 104-112]), but somewhat less attention has been focused on math anxiety interventions. Some recent studies have begun to investigate methods of reducing math anxiety (for example, see [66, 76, 113-115]) in the hopes of promoting better math performance, but future studies should continue to expand on this work. Most of this work has focused on developing interventions for math anxiety reduction in adults, including via desensitization to math content and reappraisal of physiological arousal, to help participants decrease math anxiety during math testing situations. Relatedly, unpacking the etiology of math anxiety and how negative affective reactions to math develop over time will be critical for future research, so that interventions can be developed that interrupt these processes at key times in development.

Our data set allowed us to conduct exploratory analyses to test whether the patterns of association between math anxiety and math performance differ between different subdomains of math, and as such we were able to examine specificity between math anxiety and different types of math performance. By probing each math outcome separately, we found that although math anxiety predicted math performance overall, this effect seems to be driven predominantly by performance on the Arithmetic Fluency, Procedural Calculation, and Mental Representations subtests. Math anxiety was unrelated to performance on the Word Problems subtest used in the present study. This result is surprising given previous work that typically finds math anxiety is most strongly related to performance on advanced problem-solving tasks compared to calculation tasks ([116]; see [117], for a meta-analysis). One possibility for this discrepancy lies in the different math anxiety and math performance measures used across studies. A recent meta-analysis examining the association between math anxiety and math performance found that the math anxiety scale and math performance assessment used modulates the strength of the association, such that when certain scales and tasks are used the relation between math anxiety and math performance is stronger than when these constructs are measured using other scales and tasks [117]. However, regardless of the scales or tasks used, math anxiety and math performance were typically significantly correlated across studies. Nonetheless, future work should continue to examine how and why math anxiety is related to various types of math performance, how various operationalizations of math anxiety and math performance influence whether or not the math anxiety-math performance link is found, and under which circumstances math anxiety may be particularly detrimental to math performance.

Notably, however, we only examined one affective predictor of math performance here, yet individuals may have many other ways of thinking or feeling about math beyond just anxiety. Future work will need to determine whether these findings are consistent when examining other affective factors relating to math, such as whether math attitudes may also be uniquely related to math performance (see [118] for a meta-analysis examining the association between math attitudes and math performance). There are likely many individuals who are not particularly anxious about math but nonetheless do not enjoy doing math or have other negative feelings toward math. These attitudes may be less salient to individuals when completing math tasks, and so they may also lead to different patterns of relations with math performance (or perhaps they, too, show poor math performance despite not being particularly anxious about it). Alternatively, there may be individuals who are anxious about doing math, but still have positive attitudes toward, self-concept, motivation, or beliefs about the subject, which may lead to yet another distinct pattern of associations with math performance (see [76]). For example, positive attitudes, self-concept, motivation, or beliefs about math being important or valuable may buffer against the negative effects of math anxiety on math performance and thus be a source of resilience for math anxious individuals. By examining more varied affective predictors of math performance, and their unique contributions to math performance, we will be able to identify those who are most at risk of poor math performance and develop more targeted interventions.

Weaker Independent Relations Between Cognitive Predictors and Math Performance

In contrast to previous work finding links between inhibitory control and math performance (e.g., [5, 8, 9, 14-18, 119, 120]) and between the ANS and math performance (e.g., [6, 27-32]), here we found that neither cognitive predictor was significantly related to math performance when we controlled for the other and for math anxiety. Furthermore, even when examining the math outcomes separately, rather than altogether, we saw no significant effects of inhibitory control or ANS performance on math performance in the tested subdomains.

Why might this be? It is possible that the stronger interrelations of these cognitive factors with each other than with math anxiety led to less unique explanatory power for each, but this explanation is not well-supported by the data collected in this study. Even at the bivariate level, inhibitory control and ANS performance were largely unrelated to the math outcomes measured here. These correlations were also inconsistent with some prior work (e.g., [79-82, 86-88]), as inhibitory control and ANS performance were unrelated to math anxiety at both the bivariate level and in structural models.

This may be due to several factors, including different ways that the ANS and inhibitory control have been measured across studies, as well as the different methods for assessing math anxiety, and different control variables included in various studies, as well as different analytic approaches taken. In an attempt to consider these methodological differences, particularly based on previous work finding that different stimuli used in ANS tasks show different associations with math performance [11], here we used two different measures of ANS performance, two measures of inhibitory control, and four measures of math performance to create latent variables of these constructs (as opposed to using only one measure of each construct, as has been typically done in prior work). However, follow-up analyses using only one version of the ANS stimuli showed the same pattern of results for Panamath and G&R stimuli as those reported in the main structural models, and we also saw no difference in the pattern of results based on the various subdomains of math performance (i.e., ANS performance and inhibitory control were not significantly predictive of any of the subdomains of math performance). Notably, one previous study in adults found that math anxiety moderates the association between ANS acuity and applied word problem solving performance [86], whereas another study in adults found that math anxiety mediates the association between ANS acuity and math performance [87]. It is possible that similar associations could be hidden in this dataset that we are unable to identify based on the current analytic approach.

One additional explanation for our somewhat unexpected findings regarding the cognitive predictors may lie in the developmental stage at which this study was conducted. Most of the prior work linking the ANS and inhibitory control with math performance has been in younger children (e.g., [8, 9, 77]). As such, perhaps these relations are different throughout development, explaining the inconsistent findings. While here we find that math anxiety is the strongest predictor of math performance, and inhibitory control and the ANS are largely unrelated to math performance in our homogenous sample of college students, it is possible that perhaps for younger children these associations look different. For example, when learning foundational math skills in early childhood, perhaps inhibitory control and the ANS are much more important and closely linked to math performance, whereas math anxiety may not be as strongly related. Some meta-analytic work indicates that the strength of associations between the ANS and math performance are weakly moderated by age, such that associations are strongest among children [6]. Although this possibility has not been explicitly tested with regard to the links between inhibitory control and math performance, many of the theoretical accounts of how inhibitory control would support math learning relate to how children learn in the classroom environment (see [17]). Further work examining these cognitive and affective predictors of math performance throughout development will help elucidate these associations and their potential change in explanatory power over time, leading to the most appropriately targeted interventions.

Limitations, Conclusions and Future Directions

A few limitations of this study warrant discussion and suggestions for future work. First, we examined only two cognitive factors (inhibitory control and ANS acuity) and one affective factor (math anxiety) predicting math performance. It would be useful for future work to continue to examine other possible cognitive and affective factors. For example, it is necessary to examine whether our results are consistent (with math anxiety being the strongest predictor of math performance) when probing other executive functioning skills, like working memory and cognitive flexibility. Similarly, examining other affective factors, including math attitudes, will be useful for understanding whether math anxiety itself, or affective factors more broadly, are unique predictors of math performance.

Additionally, our sample was comprised of university students. Future work corroborating these results with other samples, including adults who are not currently enrolled in school and may not have as frequent formal math experience, would be useful. Furthermore, examining these factors throughout development will prove helpful for understanding whether cognitive and affective predictors are more or less strongly related to math performance at different stages in development when learning different types of math skills. It seems plausible that earlier in development, when children are learning foundational math skills, the more basic cognitive factors like ANS acuity and inhibitory control would be more closely related to their math performance. This is likely given that ANS acuity and inhibitory control are also refined throughout early development (see [26]; [121]). Whereas once individuals are older and have more experience with math, these basic cognitive abilities may not be as influential, and perhaps math anxiety and affective factors play a larger relative role.

Nonetheless, in sum, we find that math anxiety is the strongest predictor of individuals' math performance, above and beyond their inhibitory control and ANS acuity. In fact, math anxiety alone significantly related to college students’ math performance, underscoring the importance of affective factors for math abilities. It is notable that these associations were documented in adults and in a relatively low stakes testing environment (i.e., as part of a research study rather than math grades or standardized test performance), demonstrating the developmentally pervasive and widespread implications for math anxiety. These findings provide useful targets for future investigation and interventions aimed at improving math performance. Although more work is needed to examine whether these results are consistent across other samples, this work suggests that when considering math performance and ways to support math development, including affective factors in addition to cognitive factors is an important step.

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Figure Legends

Figure 1: *Confirmatory Factor Analysis displaying standardized loadings and correlations.*

Figure 2: *Results from structural model displaying standardized loadings and correlations.* $^{*}p < .05$, $^{**}p < .01$

Figure 3: *Results from structural model predicting arithmetic fluency performance displaying standardized loadings and correlations.* $^{*}p < .05$

Figure 4: *Results from structural model predicting procedural calculations performance displaying standardized loadings and correlations.* $^{*}p < .05$

Figure 5. *Results from structural model predicting mental representations performance displaying standardized loadings and correlations.* $^{\dagger}p < .10$, $^{*}p < .05$

Figure 6: *Results from structural model predicting word problems performance displaying standardized loadings and correlations.* $^{\dagger}p < .10$, $^{*}p < .05$