

Positive Attitude Toward Math Supports Early Academic Success: Behavioral Evidence and Neurocognitive Mechanisms

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Abstract

Positive attitude is thought to impact academic achievement and learning in children, but little is known about its underlying neurocognitive mechanisms. Using a large behavioral sample of 240 children, we found that positive attitude toward math uniquely predicted math achievement, even after we accounted for multiple other cognitive-affective factors. We then investigated the neural mechanisms underlying the link between positive attitude and academic achievement in two independent cohorts of children (discovery cohort: $n = 47$; replication cohort: $n = 28$) and tested competing hypotheses regarding the differential roles of affective-motivational and learning-memory systems. In both cohorts, we found that positive attitude was associated with increased engagement of the hippocampal learning-memory system. Structural equation modeling further revealed that, in both cohorts, increased hippocampal activity and more frequent use of efficient memory-based strategies mediated the relation between positive attitude and higher math achievement. Our study is the first to elucidate the neurocognitive mechanisms by which positive attitude influences learning and academic achievement.

Keywords

mathematics achievement, attitudes, learning, childhood development, brain

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Positive attitude, encompassing strong interests and beliefs in one's ability, is thought to have a significant influence on a child's academic learning and success (Pinxten, Marsh, De Fraine, Van Den Noortgate, & Van Damme, 2014; Zimmerman, Bandura, & Martinez-Pons, 1992). This influence has been most extensively investigated in the domain of mathematics, where positive attitude has been linked to higher classroom achievement and higher scores on standardized tests (Aiken, 1976; Aiken & Dreger, 1961; Stankov & Lee, 2014; Zimmerman et al., 1992). Critically, despite decades of behavioral research, nothing is known regarding the underlying neurocognitive mechanisms by which positive attitude impacts learning and problem-solving skills in young children. Knowledge of the neurobiological factors that underlie the relationship between positive attitude and academic achievement is important for (a)

identifying specific psychological and cognitive factors that improve academic learning and (b) enabling students to reach their maximum potential.

The seminal work of Lewis Aiken in the 1960s first demonstrated that math achievement is associated with strong interest in math (Aiken & Dreger, 1961). Since then, a number of studies have demonstrated that strong interest and self-efficacy in math have a significant impact on children's academic achievement (Lee,

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Ning, & Goh, 2014; Marsh & Yeung, 1997; Pinxten et al., 2014; Seaton, Parker, Marsh, Craven, & Yeung, 2014). However, the majority of these studies have not controlled for key cognitive and affective factors that are also known to influence math achievement, such as IQ, working memory, general attitudes outside of the math domain, and anxiety. This is an important consideration because these cognitive-affective factors are known to influence math abilities (Geary, 2011; Wu, Barth, Amin, Malcarne, & Menon, 2012), limiting our understanding of the unique contribution of positive attitude toward math (PAM) on math learning and achievement (Lee et al., 2014; Stankov & Lee, 2014). We address this critical gap in the literature by investigating the impact of positive attitude on math achievement in a large group of children, carefully controlling for the potential confounding effects of cognitive and affective factors, including IQ, working memory ability, general attitude toward academics (GAA), and anxiety. We consider this a necessary and crucial step to identify cognitive and brain processes that mediate the relationship between positive attitude and math achievement.

Behavioral studies have suggested that positive attitude can reduce anxiety about learning, enhance motivation to succeed (Aiken, 1976), and boost persistence and effort during learning (Pajares & Miller, 1994; Singh, Granville, & Dika, 2002). There is also evidence showing that positive emotions are associated with increased cognitive capacity and enhanced memory performance during learning (Valentijn et al., 2006), suggesting that brain systems involved in affect, motivation, learning, and memory may be important; however, the nature of their contributions is yet to be characterized. Indeed, the extant neuroimaging literature provides clues regarding which brain systems may underlie the influence of positive attitude on improved academic learning. For example, functional MRI (fMRI) studies in adults have shown that personally salient and rewarding stimuli are better remembered and engage the affective-motivational system anchored in the amygdala and ventral striatum as well as the learning-memory system anchored in the medial temporal lobe (MTL), including the hippocampus (Dolcos, LaBar, & Cabeza, 2004; Yonelinas & Ritchey, 2015). Furthermore, in adults, greater curiosity and interest have been linked to increased responses in the ventral striatum and hippocampus (Gruber, Gelman, & Ranganath, 2014), and self-perceived abilities have been linked with enhanced memory performance and increased engagement of the MTL (Kao, Davis, & Gabrieli, 2005). Taken together, the extant behavioral and neuroimaging literature suggests that the affective-motivational and learning-memory brain systems may mediate the relationship between positive attitude and enhanced learning. However, this

has never been directly examined, nor do we know the relative contributions of these systems. This knowledge may be important in improving educational outcomes in children.

The goals of the current study were to clarify the nature of the relationship between positive attitude and academic achievement while controlling for other factors and to elucidate the underlying neurocognitive mechanisms. We first used a comprehensive battery of neuropsychological assessments in a large sample of elementary school children ($N = 240$; ages 7–10 years) to determine the unique contribution of domain-specific measures of positive attitude on children's math achievement. We then tested the hypothesis that PAM can predict children's math achievement even after controlling for cognitive and affective factors, including IQ, working memory, general and domain-specific anxiety, and GAA. These behavioral results anchored our analysis of the neurocognitive mechanisms underlying positive attitude and early academic success.

Next, using two independent cohorts ($N = 75$; discovery cohort: $n = 47$, replication cohort: $n = 28$) of children that solved arithmetic problems in the MRI scanner, we investigated whether positive attitude is associated with enhanced neural response in affective-motivational and learning-memory systems. Our use of two independent cohorts allowed us to test the replicability, reliability, and robustness of our findings.

Following the extant literature, we focused our analysis on two putative neurocognitive systems: (a) the affective-motivational system anchored in the amygdala and the ventral striatum and (b) the learning-memory system anchored in the hippocampus and adjoining MTL. We then used structural equation modeling to clarify the specific pathways and further elucidate the nature of the neural mechanisms by which PAM influences academic achievement. Critically, we demonstrate a novel role for the hippocampus in mediating the effect of PAM on efficient problem-solving skills and math achievement. Our findings provide new insights into the neurobiological mechanisms by which positive attitude operates in the human brain.

Method

Participants

Two hundred forty children (114 females, 126 males; age: range = 6.92–10.75 years, $M = 8.19$, $SD = 0.68$; see Table 1) were recruited in the San Francisco Bay area and participated in the behavioral components of this study. None of the participants had a history of psychiatric illness, neurological disorders, or learning disabilities. All protocols were approved by the institutional

Table 1. Participant Demographics and Neuropsychological Assessments by Gender

Variable	Male (<i>n</i> = 126)	Female (<i>n</i> = 114)	Comparison between genders (<i>p</i>)	All (<i>N</i> = 240)
Age in years	8.20 (0.65)	8.20 (0.67)	.706	8.2 (0.65)
Full-Scale IQ–WASI	115.5 (16.16)	113.1 (16.24)	.255	114.4 (16.21)
Achievement–WIAT-II				
Word Reading	111.6 (12.86)	111.7 (12.89)	.964	111.7 (12.84)
Reading Comprehension	108.1 (13.66)	108.9 (12.83)	.663	108.5 (13.25)
Numerical Operations	112.0 (17.42)	108.8 (17.38)	.164	110.5 (17.44)
Mathematical Reasoning	118.2 (15.51)	110.5 (16.59)	< .001	114.6 (16.45)
Working memory–WMTB-C				
Digit Recall	106.0 (16.60)	104.9 (17.46)	.647	105.5 (16.97)
Block Recall	97.6 (15.81)	99.1 (14.22)	.457	98.3 (15.06)
Counting Recall	89.4 (19.35)	91.0 (18.85)	.524	90.1 (19.09)
Backward Digit Recall	96.6 (16.16)	100.1 (16.91)	.105	98.28 (16.58)
CBCL				
Anxious/Depressed subscale	53.2 (5.19)	54.7 (6.19)	.050	53.9 (5.72)
Withdrawn/Depressed subscale	54.3 (5.89)	53.7 (5.31)	.413	54.0 (5.61)
DSM-Oriented Anxiety subscale	52.8 (4.83)	54.1 (5.76)	.086	53.4 (5.32)
SEMA	0.64 (0.55)	0.79 (0.56)	.041	0.71 (0.56)
Positive-attitude assessment				
Math (PAM)	2.87 (0.83)	2.70 (0.85)	.120	2.79 (0.84)
General academics (GAA)	2.81 (0.71)	2.97 (0.56)	.058	2.88 (0.66)

Note: The table presents means, unless otherwise indicated (standard deviations are given in parentheses). WASI = Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999); WIAT-II = Wechsler Individual Achievement Test–Second Edition (Wechsler, 2001); WMTB-C = Working Memory Test Battery for Children (Pickering & Gathercole, 2001); CBCL = Child Behavior Checklist for Ages 6–18 (Achenbach & Rescorla, 2001); SEMA = Scale for Early Mathematics Anxiety (Wu, Barth, Amin, Malcarne, & Menon, 2012); PAM = positive attitude toward math; GAA = general attitude toward academics.

review board at Stanford University, and participants were treated in accordance with the American Psychological Association Code of Conduct.

Two cohorts of children participated in brain-imaging studies involving task-based fMRI scanning. Cohort 1, the discovery cohort, was a subgroup of the original 240 participants and consisted of 53 children who volunteered in the fMRI study. Six children in Cohort 1 were excluded because of artifacts in their fMRI data, which resulted in a final sample of 47 children (25 females, 22 males; age: $M = 8.24$ years, $SD = 0.67$) who performed a block-design fMRI task that involved single-digit-addition problem solving (Young, Wu, & Menon, 2012; also see the Supplemental Material available online). Cohort 2 was an independent replication data set comprising 28 children who participated in a different study (details of this cohort are in the Supplemental Material) and was used to determine the replicability of findings regarding neurocognitive mechanisms underlying positive attitude. Cohort 2 (15 females, 13 males; age: $M = 8.70$ years, $SD = 0.48$) performed an event-related fMRI task that also involved single-digit-addition problem solving, allowing us to

investigate the effect of positive attitude on correctly and incorrectly solved problems separately.

Measures

Neuropsychological assessment. A comprehensive standardized battery of neuropsychological assessments was administered to each participant, including a demographic questionnaire, the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) to assess IQ, the Wechsler Individual Achievement Test–Second Edition (WIAT-II; Wechsler, 2001) to measure mathematical and reading abilities, and the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001) to assess working memory capacity. We used two subscales from the WIAT-II for standardized math achievement scores: Numerical Operations for computational skills in arithmetic problems and Math Reasoning for solving more complex word problems. The Word Reading and Reading Comprehension subscales from the WIAT-II were used to assess reading abilities. Parents and guardians also completed the Child Behavior Checklist for Ages 6–18 (Achenbach & Rescorla, 2001) to assess domain-general

behavioral and emotional problems. Syndrome Subscale 1 (Anxious/Depressed), Syndrome Subscale 2 (Withdrawn/Depressed), and the DSM-Oriented Anxiety subscale were used to detect any anhedonic or anxiety-related traits. The Scale for Early Mathematics Anxiety (Wu et al., 2012) was used to assess domain-specific anxiety related to early experiences of learning math (see Table 1).

Positive attitude. A short survey of 12 questions based on the Self Description Questionnaire (Marsh & O'Neill, 1984) was designed to assess positive attitude in children. Six questions measured two aspects of PAM, namely, strong interests (e.g., "How much do you like math?") and self-perceived ability (e.g., "How good are you at learning math?"), and six questions measured positive attitude toward general academics. Participants were asked to respond on a 5-point Likert-type scale of *not at all*, *a little*, *somewhat*, *very*, and *very very*. (For a complete list of the questions, see Table S1 in the Supplemental Material.) A mean score averaging responses on the six math-related questions and a mean score on the remaining six questions (range = 0–4) were calculated to determine PAM and GAA scores, respectively.

Problem-solving-strategy assessment. Arithmetic-problem-solving strategies were assessed outside the scanner for children who participated in the neuroimaging study. Children answered 18 simple addition problems, and the experimenter recorded the children's reaction time, verbal response, and strategy report (Siegler, 1987; see Fig. 1a). Retrieval rate was computed as the proportion of trials in which the child correctly answered the problem using a direct retrieval strategy. This measure, which has been shown to correlate with later math achievement, served as an index of the mastery of basic math facts (Geary, 2011).

fMRI data acquisition and preprocessing

Functional brain images were acquired on a 3T Signa scanner (General Electric, Milwaukee, WI) using a custom-built head coil at the Stanford University Richard M. Lucas Center for Imaging. Head movement was minimized during the scan by cushions placed around the participant's head. A total of 29 axial slices (4.0-mm thickness, 0.5-mm skip) parallel to the anterior commissure-posterior commissure line and covering the whole brain were imaged using a T2*-weighted gradient echo spiral in-out pulse sequence (Lai & Glover, 1998) with the following parameters: repetition time = 2 s, echo time = 30 ms, flip angle = 80°, 1 interleave. The field of view was 20 × 20 cm², and the matrix size was 64 × 64,

providing an in-plane spatial resolution of 3.125 mm. To reduce blurring and signal loss from field inhomogeneity, we used an automated high-order shimming method based on spiral acquisitions before acquiring fMRI scans (Kim, Adalsteinsson, Glover, & Spielman, 2002).

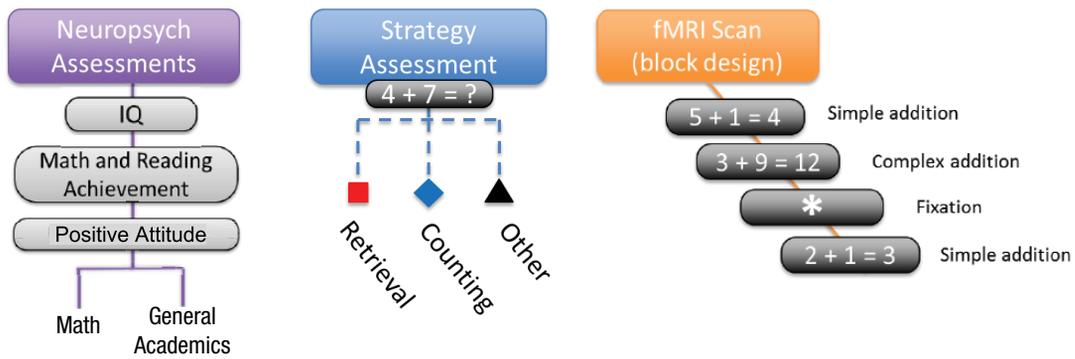
Data were analyzed using a general linear model implemented in the Statistical Parametric Mapping program (SPM8; Wellcome Trust Centre for Neuroimaging, London, United Kingdom). Images were realigned to correct for movement, denoised, spatially normalized to Montreal Neurological Institute (MNI) space, and smoothed with an effective Gaussian kernel of 6 mm. A set of linear regression analyses revealed that PAM scores were not correlated with any of the six movement measures (x , y , z , pitch, roll, and yaw; all $ps > .05$).

Statistical analysis of fMRI data

Individual statistics. Task-related brain responses in the block-design data from Cohort 1 were identified using the general linear model implemented in SPM8. In the individual-subject analyses, interpolated volumes flagged at the preprocessing stage were deweighted in subsequent analyses. For the addition task, brain activity related to each condition was modeled using boxcar functions corresponding to the block length and convolved with a canonical hemodynamic response function and a temporal dispersion derivative to account for voxel-wise latency differences in hemodynamic response. Low-frequency drifts at each voxel were removed using a high-pass filter (0.5 cycle/min). Serial correlations were accounted for by modeling the fMRI time series as a first-degree autoregressive process. Voxel-wise t -statistics maps contrasting the complex-addition and fixation conditions (complex – fixation) were generated for each participant.

To test our hypotheses related to the affective-motivational and MTL learning-memory systems, we applied a small volume correction (Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004) to identify amygdala and hippocampus clusters in which task-related activation was significantly correlated with individual PAM scores. Given our a priori hypotheses about these subcortical regions, we used a height threshold of $p < .05$ and an extent threshold of $p < .05$, corrected for multiple comparisons based on nonstationary suprathreshold cluster-size distributions using Monte Carlo simulations. Masks derived from the Automated Anatomical Labeling atlas (Tzourio-Mazoyer et al., 2002) were used to ensure that the clusters were localized to the respective regions of interest (ROIs). Additional power analyses were conducted to ensure that the sample size in both cohorts was sufficient to detect these effects (see the Supplemental Material).

a



b

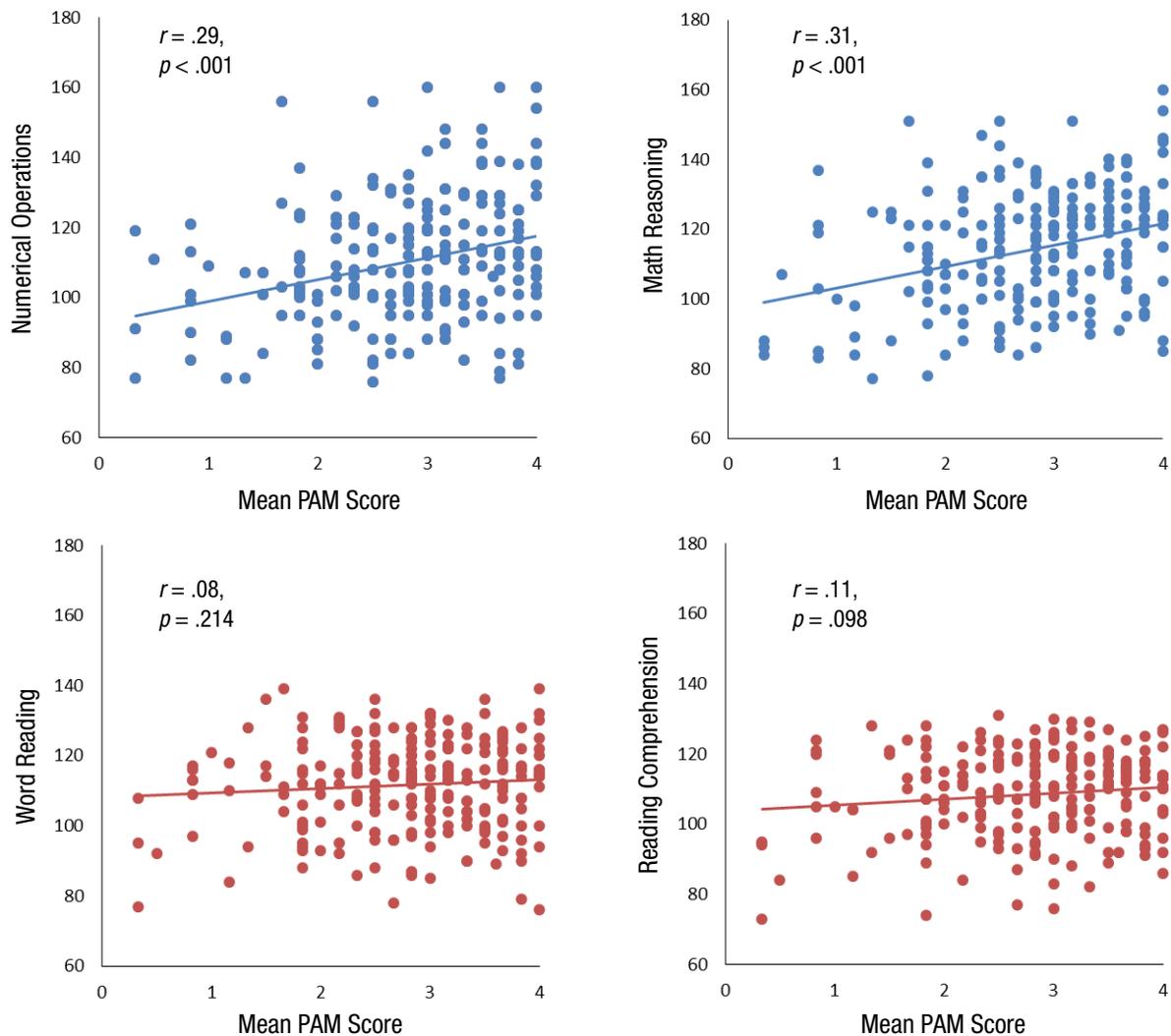


Fig. 1. Overall study design in Cohort 1 and behavioral results. In this study, (a) 240 children underwent extensive neuropsychological assessments of cognitive abilities and attitude. Fifty-three participated in the functional MRI (fMRI) study and completed a session designed to assess use of efficient memory-based strategies. The scatterplots (b; with best-fitting regression lines) show the relation between each of four measures of academic achievement and mean positive attitude toward math (PAM) score. Measures of academic achievement were obtained from the four standardized subscales of the Wechsler Individual Achievement Test–Second Edition (Wechsler, 2001).

ROI definition. To conduct additional analyses, including the structural equation modeling described below, and to visualize the results, we defined ROIs with a diameter of 2 mm in hippocampal regions that showed significant effects in Cohorts 1 and 2. These functionally specified ROIs in Cohort 1 were also used for Bayesian estimation analysis with Markov chain Monte Carlo (MCMC) permutations (Plummer, 2014), which provide complete distributions for credible values of correlation between the two measures of interest—brain activation and PAM. We used prior literature to define the amygdala (Gur et al., 2002) and ventral striatum (Di Martino et al., 2008) to examine the null relation in these regions with positive attitude in Cohorts 1 and 2. To ensure that all ROIs were localized within each subcortical structure of interest, we used 2-mm-diameter ROIs centering on peak coordinates, shown in Table S4 in the Supplemental Material. These ROIs were also used for MCMC permutations to confirm null results in the affective-motivational system.

Functionally determined masks of the right hippocampal ROIs were created for Cohorts 1 and 2 for prediction analysis using balanced cross-validation combined with linear regression (Supekar, Iuculano, Chen, & Menon, 2015; see the Supplemental Material). Inclusive masks were created by thresholding the activation cluster within right lateral hippocampal activation clusters in Cohorts 1 and 2 at $\alpha = .05$.

Structural equation modeling of brain-behavior relations. We used structural equation modeling to investigate the neurocognitive mechanisms by which PAM influences efficient problem solving and academic achievement. Structural equation modeling was conducted using the *Lavaan* package (Version 0.5-17) in the R programming environment (Version 3.2.2; R Core Team, 2015). Specific models were constructed to investigate how brain activation mediates the influence of PAM on math achievement. Averaged beta values from each ROI were used for model fitting, and significant path estimates were used to assess relations between variables. Conventional measures, such as the chi-square test, comparative fit index (CFI), Tucker-Lewis index (TLI), and root-mean-square error of approximation (RMSEA), were used to assess model fit, and the Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to choose the best-fitting models from different alternatives. Although structural equation modeling uses directional predictive paths, it cannot be used to infer causality in cross-sectional data. Alternative models with bidirectional paths were also tested to examine improved or weakened model fit (see the Supplemental Material). Finally, power analyses were conducted using Monte Carlo simulations implemented in the R package *simsem* (Pornprasertmanit, Miller, & Schoemann, 2013), as detailed in the Supplemental Material.

Results

Positive attitude predicts math achievement

PAM scores were positively correlated with both math achievement measures of the WIAT-II—Numerical Operations, $r(233) = .29, p < .001$, 95% confidence interval (CI) = [.17, .41], and Math Reasoning, $r(233) = .31, p < .001$, 95% CI = [.19, .42]—but not with reading achievement measures ($p > .05$ for both measures; see Fig. 1b). No such effects were observed with GAA (see Table S3 and Fig. S2 in the Supplemental Material). These results were consistent with findings from our factor analysis that revealed PAM to be distinct from GAA (see the Supplemental Material). Critically, the association between PAM and math achievement remained significant after age, IQ, working memory, and math anxiety were controlled for in a multiple regression analysis, and no such significant relationship was observed between PAM and reading abilities (see Table 2). Additional analysis using the two subcomponent scores of the PAM, strong interest and self-perceived ability, indicated that both subcomponent scores predicted children's math abilities (see Table S4).

PAM was associated with enhanced hippocampal response in two independent cohorts

In Cohort 1, we found that PAM was positively correlated with task-related activity in the bilateral hippocampus (peak MNI coordinates: $x = 38, y = -22, z = -16$ and $x = -36, y = -14, z = -26$; small-volume correction $p < .05$). ROI analysis showed that PAM scores were correlated with activation in the right hippocampus, $r(45) = .39, p = .006$, 95% CI = [.12, .61], and the left hippocampus, $r(45) = .37, p = .011$, 95% CI = [.09, .59] (Fig. 2a), and this effect remained robust even after IQ, age, working memory, and math anxiety were controlled for (see Table S5 in the Supplemental Material). A significant relation between PAM and hippocampal activation was further supported by Bayesian estimation analysis with MCMC simulation (Plummer, 2014; see Fig. S3 in the Supplemental Material).

In Cohort 2, an event-related design allowed us to investigate the relation between PAM for both correctly and incorrectly performed trials. In accordance with our prediction based on the results from Cohort 1, we found that PAM scores in Cohort 2 were positively correlated with task-related responses in two clusters within the right hippocampus. One largely overlapped with the right hippocampal cluster detected in Cohort 1 (peak coordinates: $x = 38, y = -20, z = -12$), $r(26) = .41, p < .05$, 95% CI = [.04, .68]. Furthermore, PAM scores

Table 2. Results From the Multiple Regression Analysis of Positive Attitude Toward Math Scores and Individual Differences in Math and Reading Achievements

Predictor	Achievement–WIAT-II											
	Numerical Operations (<i>n</i> = 216)			Math Reasoning (<i>n</i> = 216)			Word Reading (<i>n</i> = 217)			Reading Comprehension (<i>n</i> = 215)		
	β	<i>SE</i>	<i>t</i>	β	<i>SE</i>	<i>t</i>	β	<i>SE</i>	<i>t</i>	β	<i>SE</i>	<i>t</i>
Age	−0.00	0.06	−0.02	−0.04	0.07	−0.87	−0.11	0.06	−1.78	0.10	0.06	1.59
IQ	0.28	0.07	3.93***	0.54	0.05	10.44***	0.45	0.06	6.95***	0.54	0.07	8.17***
Gender	0.17	0.13	1.35	0.37	0.09	3.93***	0.06	0.12	0.50	−0.11	0.12	−0.92
CBCL: Anxious/Depressed	−0.11	0.10	−1.12	−0.01	0.08	−0.18	0.07	0.09	0.69	0.08	0.10	0.80
CBCL: Withdrawn/Depressed	−0.03	0.07	−0.36	−0.02	0.05	−0.46	−0.00	0.07	−0.21	−0.12	0.07	−1.68
CBCL: DSM-Oriented Anxiety	0.05	0.10	0.51	−0.01	0.07	−0.16	−0.00	0.09	−0.02	−0.03	0.09	−0.37
General attitude toward academics	−0.01	0.06	−0.18	−0.09	0.05	−1.72	−0.01	0.06	−0.15	0.00	0.06	0.03
Working memory composite	0.33	0.08	4.32***	0.22	0.06	3.99***	0.23	0.07	3.22**	0.04	0.07	0.53
Math anxiety	0.01	0.07	0.12	−0.12	0.05	−0.231*	−0.05	0.07	−0.73	0.04	0.07	0.61
Positive attitude toward math	0.22	0.07	3.23**	0.14	0.05	2.62**	−0.07	0.06	−1.11	0.07	0.07	1.08

Note: WIAT-II = Wechsler Individual Achievement Test–Second Edition (Wechsler, 2001); CBCL = Child Behavior Checklist for Ages 6–18 (Achenbach & Rescorla, 2001). Gender was coded 0 for female and 1 for male.

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

were significantly correlated with this hippocampal activation for correct, but not incorrect, trials (Figs. 2b and 2c). The other cluster was located in the anterior hippocampus proximal to entorhinal cortex (peak coordinates: $x = 12$, $y = -8$, $z = -24$), $r(26) = .56$, $p < .01$, 95% CI = [.24, .77]. These results identify a reliable and replicable relationship between PAM and right hippocampal responses associated with successful numerical problem solving.

Hippocampal activity predicts individual differences in positive attitude: cross-validation analysis

To investigate whether hippocampal responses can reliably predict individual differences in PAM scores, we used a machine-learning approach and conducted a balanced cross-validation analysis (Supekar et al., 2015; see the Supplemental Material) using activity in the right hippocampal ROI as the independent variable and individual PAM scores as the dependent variable. This analysis revealed that in both cohorts, activity in the right hippocampal cluster predicted individual PAM scores—Cohort 1: $r = .22$, $p < .001$; Cohort 2: $r = .27$, $p < .001$.

PAM was not associated with enhanced response in the amygdala and ventral striatum

We did not observe any significant relationships between PAM and brain activation associated with the

affective-motivational system, including the amygdala and ventral striatum, even after small volume correction, which was contrary to our hypothesis. To examine this further, we conducted additional analysis using a priori ROIs in the amygdala and ventral striatum and found similar null results in Cohorts 1 and 2 (see Table S7 in the Supplemental Material). These null results were further confirmed with Bayesian estimation analysis (see Fig. S3 in the Supplemental Material), demonstrating that PAM scores across individuals were specifically associated with enhanced neural responses in the learning-memory system anchored in the hippocampus/MTL rather than affective-motivational systems anchored in the amygdala and ventral striatum.

Neurocognitive mechanisms relating positive attitude, the hippocampus, and math achievement

To elucidate the neurocognitive mechanisms by which the hippocampal memory system might mediate the relation between PAM and math achievement, we tested three structural equation models. In the full-retrieval-based model, the relation between PAM and math achievement was fully mediated by hippocampal involvement, leading to enhanced use of efficient memory-based retrieval strategies (Fig. 3a). The partial-retrieval-based model was similar but also examined an alternate direct effect of PAM on math achievement (Fig. 3a). The non-retrieval-based model served as a base model in which hippocampal engagement

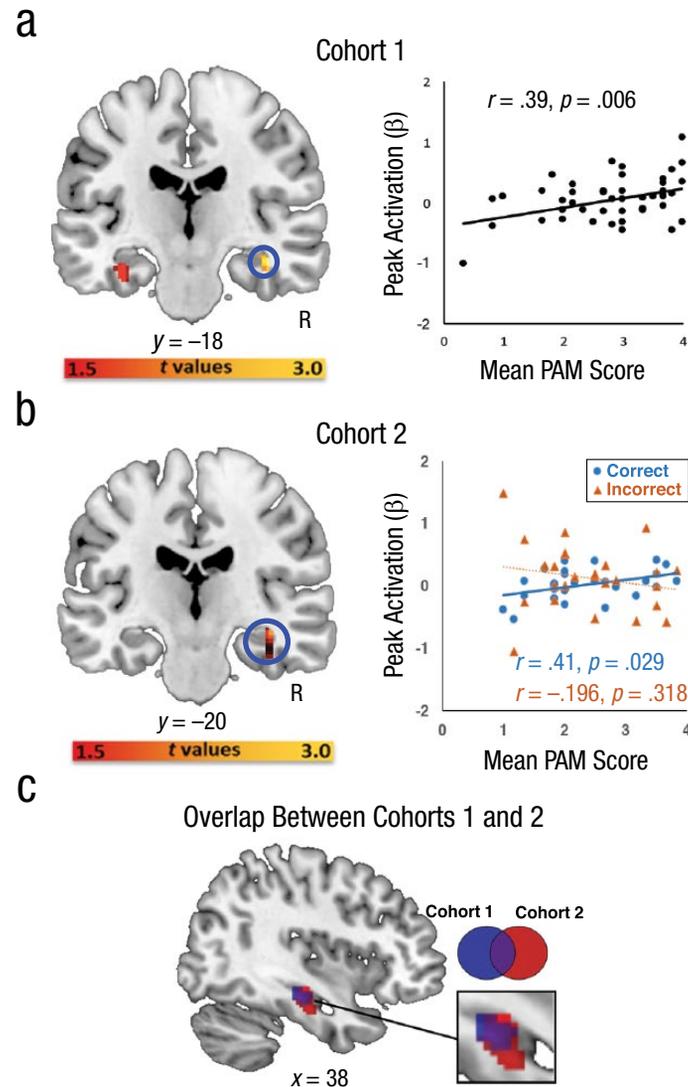


Fig. 2. Correlation between positive attitude toward math (PAM) and right hippocampal activation, separately for (a) Cohort 1 ($n = 47$), (b) Cohort 2 ($n = 28$), and (c) the overlap between Cohorts 1 and 2. The brain slices in each panel show regions with significant activation (highlighted in the blue circles). The scatterplots (with best-fitting regression lines) show (a) peak activation as a function of mean PAM score and (b) peak activation as a function of mean PAM score and trials on which problems were correctly or incorrectly solved.

mediated the relation between PAM and math achievement, independent of memory-based retrieval strategies (Fig. 3a).

In Cohort 1, the full-retrieval-mediated model with the lowest AIC and BIC values best fit the data— $\chi^2(3) = 0.03$, $p = .96$, CFI = 1.00, TLI = 1.00, RMSEA = 0.00, standardized root-mean-square residual = .002—when compared with the non-retrieval-mediated and partial-retrieval-mediated models (Fig. 3b and Table 3). In the full-retrieval-mediated model, PAM had a significant and direct effect on right hippocampal activation ($\beta = 0.39$,

$z = 2.90$, $p < .01$), which had a significant influence on retrieval rate ($\beta = 0.40$, $z = 2.87$, $p < .01$). This model suggests a significant indirect effect of PAM on retrieval rate via right hippocampal activation ($\beta = 0.19$, $z = 2.13$, $p < .05$). Furthermore, individual scores on the Numerical Operations subtest of the WIAT-II were significantly and directly affected by retrieval rate ($\beta = 0.47$, $z = 3.17$, $p < .01$). Power analysis using Monte Carlo simulations determined medium to high power (0.6–0.9) to detect these effects in both cohorts (see Table S9 in the Supplemental Material).

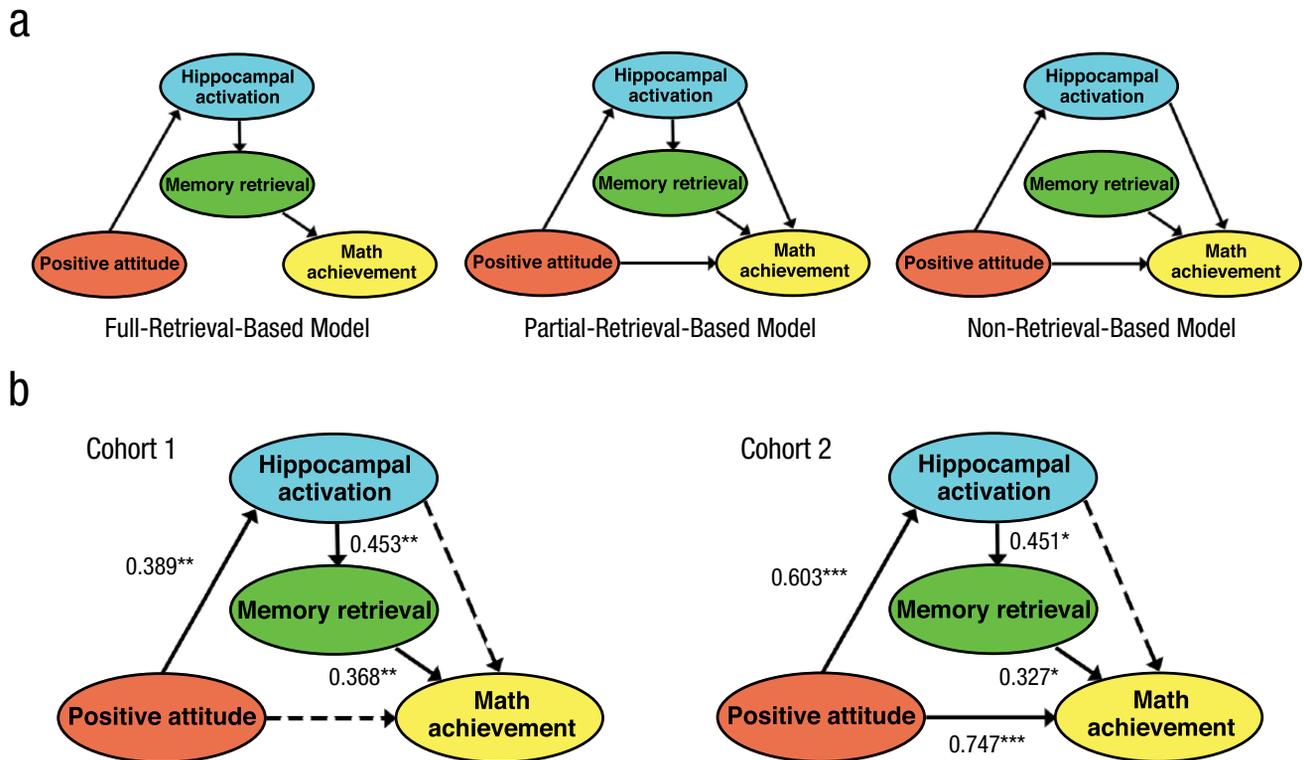


Fig. 3. Hypothetical models of the brain-behavior relationship and best-fitting models for Cohorts 1 and 2. The three possible structural equation models (a) illustrate how hippocampal activation mediates the relation between positive attitude toward math (PAM) and math achievement. The full-retrieval-based model tested the hypothesis that the effect of PAM on math achievement would be fully mediated by hippocampal activation and memory retrieval; the partial-retrieval-based model tested the hypothesis that the hippocampus may contribute to cognitive functions, including retrieval of math facts; and the non-retrieval-based model tested the hypothesis that PAM would increase activation in the hippocampus and lead to better math achievement scores independently of memory retrieval use. The best-fitting models (b) are shown for Cohort 1 and Cohort 2. The values on each path are standardized estimates of path coefficients; solid lines indicate significant paths (* $p < .05$, ** $p < .01$, *** $p < .001$), and dashed lines indicate nonsignificant paths. In all models, hippocampal activation was determined using beta values from the region-of-interest analysis in the right hippocampus, positive attitude was based on PAM scores, memory retrieval rate was assessed using strategy assessments, and math achievement represented individual scores on the Numerical Operations subtest of the Wechsler Individual Achievement Test–Second Edition (Wechsler, 2001).

Remarkably, the same pathway linking PAM with right hippocampal activation, memory retrieval, and math achievement was also significant in Cohort 2: for an indirect path from PAM to retrieval rate mediated by hippocampal activation, $\beta = 0.27$, $z = 1.992$, $p < .05$, and for a direct path from retrieval rate to math achievement, $\beta = 0.33$, $z = 2.033$, $p < .05$ (Fig. 3b). In this case, the mediation pathway was complemented by a direct path from PAM to math achievement. Additional details of the structural equation modeling analysis in Cohort 2 are in the Supplemental Material. Taken together, the two independent data sets converge on the finding that increased hippocampal response during numerical tasks mediates the relation between positive attitude and efficient problem solving, leading to academic success in children.

Discussion

This study is the first to investigate the neurocognitive mechanisms by which PAM impacts children's math

achievement. We focused on mathematical skills because of strong behavioral evidence showing that learning and achievement in this domain are prominently influenced by positive attitude (Aiken, 1976; Aiken & Dreger, 1961; Pinxten et al., 2014; Zimmerman et al., 1992). Our behavioral and fMRI data, in conjunction with structural equation modeling, revealed three key findings. First, PAM uniquely predicts individual differences in children's math achievement even after multiple general cognitive and affective factors are controlled for, and both interest and self-perceived ability, components of PAM, contribute to math achievement. Second, positive attitude is associated with increased engagement of the MTL memory system but not the affective-motivational system, and third, the hippocampus mediates the relation between PAM and numerical-problem-solving abilities. Notably, our findings implicating the MTL memory system in PAM were replicated in a second independent cohort of children. Our study provides strong evidence linking positive attitude

Table 3. Fits of the Three Hypothesized Models Shown in Figure 3 (Cohort 1)

Model	χ^2	CFI	TLI	RMSEA	SRMR	AIC	BIC
Non-retrieval-based	$\chi^2(1) = 7.583^{**}$	0.661	-0.695	0.374	0.104	534.582	558.634
Partial-retrieval-based	$\chi^2(1) = 0.875$	1.000	1.033	0.000	0.033	527.874	551.926
Full-retrieval-based	$\chi^2(3) = 3.141$	0.994	0.987	0.032	0.057	526.14	546.492

Note: Boldface indicates the lowest (best) Akaike information criterion (AIC) and Bayesian information criterion (BIC) scores. Although both the partial-retrieval-based and full-retrieval-based models reasonably fit the data, the full-retrieval-based model showed lower AIC and BIC scores with fewer parameters. CFI = comparative fit index; TLI = Tucker-Lewis index; RMSEA = root-mean-square error of approximation; SRMR = standardized root-mean-square residual.

** $p < .01$.

with math achievement and elucidates the neurocognitive mechanisms by which PAM influences learning and achievement.

Our first goal was to investigate the influence of PAM on mathematical achievement in children while controlling for crucial cognitive and affective factors. Analysis of behavioral data with a large well-characterized group of 240 children (ages 7–10 years) confirmed that PAM has a significant impact on academic achievement and that this relation holds even after IQ, working memory, and anxiety are controlled for. This result extends previous findings showing the effect of positive attitude on academic achievement (Pinxten et al., 2014; Stankov & Lee, 2014; Zimmerman et al., 1992) by demonstrating that positive attitudes make a unique contribution to academic achievement. We did not find these effects with GAA, demonstrating that domain-specific positive attitude is a critical psychological factor in academic learning. Results suggest that a crucial avenue for educational practice is to assess and improve children's attitudes toward mathematics as a way of harnessing each child's full potential and maximizing learning during the pivotal grade-school years.

Our second goal was to investigate the neurocognitive mechanisms by which positive attitude influences academic achievement. Behavioral studies dating back to the 1960s have hinted that brain systems involving affect and motivation (Pajares & Miller, 1994; Singh et al., 2002) and learning and memory (Valentijn et al., 2006) may underpin the influence of positive attitude on academic learning and achievement, but this has never been directly tested in young school-age children. Accordingly, we tested two competing and theoretically motivated hypotheses regarding the role of specific brain systems associated with PAM: the affective-motivational system anchored in the amygdala and ventral striatum (Dolcos et al., 2004) and the learning-memory system anchored in the MTL (Kao et al., 2005). In two independent cohorts of young children, who underwent functional brain imaging while performing arithmetic problem-solving tasks, we found that PAM was associated with enhanced neural activation of the

hippocampus but not the amygdala or ventral striatum. Analysis of event-related fMRI data (Cohort 2) further revealed that the PAM-related increase in hippocampal activation occurred only during correct but not incorrect trials, demonstrating the specificity of this relationship to successful numerical problem solving. These findings identify the MTL learning-memory system, and the hippocampus in particular, as a novel neural correlate of PAM and math achievement.

To further investigate the putative role of the hippocampus in mediating the effects of attitude on academic achievement, we contrasted three distinct quantitative models. These models were based on previous work relating the MTL memory system to the development of efficient memory-based retrieval of math knowledge in children (Qin et al., 2014). Memory-based retrieval is an important measure as it indexes the mastery of basic math facts and is known to be a strong predictor of later math achievement (Geary, 2011). Our structural equation models contrasted different hypotheses regarding how hippocampal activation and memory-based retrieval may mediate the effects of positive attitudes on math achievement. If hippocampal activation associated with PAM were not related to memory retrieval (Dolcos et al., 2004), hippocampal activation would have a direct impact on math achievement without mediation by retrieval skills (non-retrieval-based model). The other two models (full- and partial-retrieval-mediated models) implicate retrieval skills as a key mediating cognitive factor between positive attitude and ability. Notably, results from our structural equation modeling analysis provided strong support for the retrieval-mediated models with a significant indirect path from PAM to memory retrieval via hippocampal activation in Cohorts 1 and 2. In contrast, our structural equation modeling analysis failed to reveal a direct effect of hippocampal activation on math achievement or any association with the amygdala and ventral striatal responses in either cohort. This suggests that positive attitude may not elicit responses in the affective-motivational system in the same way as has been previously found with negative affect and

math anxiety (Young et al., 2012). This finding is novel and surprising given that behavioral studies have implicated affect regulation and motivation as a possible mechanism underlying positive attitudes and academic skills (Aiken, 1976; Pajares & Miller, 1994). However, it is possible that in the absence of explicit reward, the affective-motivational system may not be sensitive to positive attitude.

Our results suggest that learning-memory systems anchored in the hippocampus underpin the relationship between positive attitude and math achievement through enhanced mnemonic processing (Gruber et al., 2014; Kao et al., 2005). The hippocampus is known to support a wide range of mnemonic processes by integrating disparate information into meaningful representations in declarative memory and building new associations (Eichenbaum, 1999; McClelland, McNaughton, & O'Reilly, 1995). In the domain of numerical problem solving, these processes facilitate creation of associations between problems and answers and memorization of facts, and they play an essential role in skill acquisition, especially in the early stages (Qin et al., 2014). Thus, positive attitudes may lead to increased recruitment of the hippocampus to facilitate more efficient encoding and retrieval, leading to improved learning and task proficiency. More broadly, efficient memory processes may represent a general neurocognitive mechanism by which positive attitude contributes to academic achievement and learning in children.

We could not determine the direction of causal influences between positive attitude and math achievement because of the cross-sectional nature of our study (see, however, Table S10 in the Supplemental Material). To more directly address this, future studies will need to use explicit learning paradigms, cognitive interventions, and longitudinal designs to test causal links associated with the neurocognitive models uncovered in the present study, building on previous behavioral studies in related domains (Marsh & Yeung, 1997; Pinxten et al., 2014). Investigations of the relation between positive attitude and growth mind-set (Blackwell, Trzesniewski, & Dweck, 2007) and interactions between learning-memory and affective-motivational systems during reward-based learning—in typically developing children as well as in children with learning disabilities and high levels of anxiety (Wang et al., 2015)—also remain important areas for future research.

In conclusion, our study demonstrates, for the first time, that PAM in children has a unique and significant effect on math achievement independent of general cognitive abilities and that this relation is mediated by the MTL memory system. More broadly, we propose that positive attitude may upregulate brain systems involved in mnemonic processes in learning and

memory formation, thereby facilitating knowledge acquisition and academic achievement.

Action Editor

John Jonides served as action editor for this article.

Author Contributions

L. Chen and V. Menon designed the research; S. R. Bae, C. Battista, S. Qin, T. M. Evans, and L. Chen performed the research; L. Chen, S. R. Bae, and S. Qin analyzed the data; L. Chen and V. Menon wrote the manuscript; and all authors contributed to editing it.

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Declaration of Conflicting Interests

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Supplemental Material

Additional supporting information can be found at <http://journals.sagepub.com/doi/suppl/10.1177/0956797617735528>

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