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BRIEF REPORT

Choke or Thrive? The Relation Between Salivary Cortisol and Math Performance Depends on Individual Differences in Working Memory and Math-Anxiety

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In the current study, we explored how a person's physiological arousal relates to their performance in a challenging math situation as a function of individual differences in working memory (WM) capacity and math-anxiety. Participants completed demanding math problems before and after which salivary cortisol, an index of arousal, was measured. The performance of lower WM individuals did not depend on cortisol concentration or math-anxiety. For higher WM individuals high in math-anxiety, the higher their concentration of salivary cortisol following the math task, the worse their performance. In contrast, for higher WM individuals lower in math-anxiety, the higher their salivary cortisol concentrations, the better their performance. For individuals who have the capacity to perform at a high-level (higher WMs), whether physiological arousal will lead an individual to choke or thrive depends on math-anxiety.

Keywords: math-anxiety, cortisol, working memory, individual differences

Math-anxiety is characterized as an adverse emotional reaction to math or the prospect of doing math (Richardson & Suinn, 1972). For math-anxious individuals, opening a math textbook or even entering a math classroom can trigger a negative emotional response. Despite normal performance in other academic areas, people with math-anxiety perform poorly on measures of math ability in comparison to their less-math-anxious peers (Hembree, 1990).

Why is math-anxiety tied to poor math performance? One explanation is that math-anxious students are simply less skilled or practiced at math than their non-math-anxious counterparts. After all, individuals high in math-anxiety tend to avoid math classes and receive lower grades in the math classes they do take (Ashcraft & Kirk, 2001). However, there is an alternative explanation for how math-anxiety compromises math performance. Namely, in math-anxious individuals, the anxiety itself causes an online deficit in math problem solving that contributes to poor math outcomes (Ashcraft, Kirk, & Hopko, 1998).

Support for the view that people's anxiety about doing math—over and above their actual math ability—can impede their math performance comes from work by Ashcraft and Kirk (2001). These researchers examined low and high math-anxious individuals' ability to simultaneously perform a mental addition task and a memory task involving the short-term maintenance of random letter strings for later recall. Difficulty levels of both the primary math task and the secondary memory task were manipulated. Performance was worst (mainly in the form of increased math task error rates) in instances in which individuals, regardless of math-anxiety, performed both a difficult math and memory task simultaneously. However, in comparison to less math-anxious individuals, participants high in math-anxiety showed an exaggerated increase in performance errors under the difficult math and memory task condition. The authors concluded that performance deficits under demanding dual-task conditions were most pronounced in high math-anxious individuals because their emotional reaction diverted attention away from the content of the task. Similar to a demanding secondary task, this process co-opted the working memory capacity that might have otherwise been available for math performance.

Working memory (WM) is a short-term system involved in the control, regulation, and active maintenance of a limited amount of information relevant to the task at hand (Miyake & Shah, 1999). If anxiety has a disruptive effect on WM, then performance should suffer when a task relies on this system.

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Indeed, previous work supports this prediction. Beilock et al. (2004) have shown that anxiety about performing at an optimal level selectively affects performance on those math problems that place the greatest demands on WM, such as problems that involve a carry operation or the maintenance of large intermediate answers.

Moreover, individual differences in WM capacity also predict who will be most affected by stressful performance situations (Beilock & Carr, 2005). In particular, higher working memory individuals (HWMs) are most susceptible to performance decrements in stressful situations. This is because HWMs tend to employ cognitively demanding strategies during problem solving. These strategies allow HWMs to reach a greater level of performance relative to lower working memory individuals (LWMs) who employ cognitively leaner but less accurate heuristics. Yet, these cognitively demanding strategies fail when WM is compromised while heuristics yield a low but consistent level of performance (Beilock & DeCaro, 2007). Thus, there is considerable evidence to suggest that diversion of WM, perhaps toward worries about the task, is one mechanism behind the online deficits associated with math-anxiety (Beilock, 2008).

Although anxiety plays an important role in the expression of poor performance, it may not be the only factor. For instance, while math-anxious individuals report anxiety in math-related situations, they also exhibit intense physiological reactions, such as a pounding heart, sweaty palms and even shaking hands (as in Ashcraft, 2002), that may be related to their affective response. In the current work we explore the relation between these physiological reactions and math performance.

Two-Factor Theory of Emotion

Our approach is motivated by work in the social psychology literature (Schachter & Singer, 1962). According to Schachter and Singer's two-factor theory, individuals perceive an emotional event based on a cognitive interpretation of internal physiological cues. For example, if a person experiences sweating palms and a racing heart, the two-factor theory argues that one's interpretation of these cues discriminates between the subjective feeling of fear and that of love (see also, Macdowell & Mandler, 1989). Given a potentially stressful situation such as math problem solving, whether an individual chokes or thrives may similarly depend on their interpretation of their physiological state. While many individuals have heightened physiological responses in a math performance situation, math-anxious individuals in particular may be likely to interpret this physiological reaction negatively and thus perform poorly. In contrast, nonanxious individuals might even benefit from a heightened physiological state if they interpret their physiological reaction to indicate a challenging performance situation.

Present Research

In the current work, participants solved a set of difficult math problems. To assess how our participants might construe this potentially stressful situation, we also measured their trait math-anxiety. Because math-anxiety taps into an individual's explicit anxiety about math, it is an appropriate gauge of how they would react to a challenging math situation. We also asked participants to complete a WM capacity measure. Last, we sampled salivary cortisol concentrations in our participants both before and after the math test as an index of their physiological response to performing the task.

We selected the hormone cortisol because it is often associated with stressors in humans and is thought to have effects on WM (Duncko, Johnson, Merikangas, & Grillon, 2009; Elzinga & Roelofs, 2005; Lupien, Gillin, & Hauger, 1999). Recent animal research supports this idea (Roozendaal, McReynolds, & McGaugh, 2004). In Sprague–Dawley rats, corticosterone (the analogous hormone in rats) has been shown to act on the prefrontal cortex to cause a deficit in performance on the delayed response T maze (a putative measure of WM). Critically, this deficit depends on input from the basolateral amygdala, a key region in emotional processing (LeDoux, 2000). When input from this region is interrupted by a lesion or blocked by a receptor antagonist, the corticosterone-driven deficit disappears. This has lead to the claim that the negative effects of corticosterone on WM depend on emotional processing. Although not definitive, this work suggests cortisol as a potential link between people's anxiety about a math situation, their WM capacity, and their math performance.

We used *modular arithmetic* (Bogomolny, 1996) as our math task. The object of modular arithmetic (MA) is to judge the validity of problems such as $51 \equiv 19 (mod\ 4)$. One way to solve MA is to subtract the middle number from the first number (i.e., 51–19) and then divide this difference is by the last number (32/4). If the dividend is a whole number, the answer is "true." MA is a desirable math task because it is novel, challenging, and its WM demands can be easily manipulated by varying the size of the numbers and whether or not problems involve a borrow operation.

In summary, the two-factor theory allows us to make specific predictions about which individuals will choke and which will thrive in our math performance situation. Individuals that interpret the situation negatively (high math-anxious individuals) will suffer as the intensity of their physiological response increases. However, this same physiological intensity might actually contribute to facilitated performance for those low in math-anxiety.

Critically, the relationship between math-anxiety, cortisol, and performance should depend on individual differences in WM. This is because the demanding strategies that HMWs often apply in math performance situations are compromised when WM is impaired. If problem solvers interpret their physiological response as indicative of math-related distress, this interpretation may hinder one's ability to execute demanding computations in WM. In contrast, because HWMs' demanding strategies should benefit from increased availability of WM resources, HWMs may be in a unique position to gain from a favorable emotional interpretation of their physiological response.

Method

Participants

Participants ($N = 73$; 29 male, 44 female) were recruited from University of Chicago, Roosevelt University, and the local area (age $M = 23.03$, $SD = 5.42$, range = 18–42). Participants were also screened for the use of psychiatric medications and adrenal dysfunction.[1]

Working memory capacity. Participants' performance on the automated Reading Span (RSPAN; Conway et al., 2005), a common WM measure, served as our measure of WM capacity.

In the RSPAN, participants read a series of sentences followed by letters (e.g., "On warm sunny afternoons, I like to walk in the park.R"), and judge whether each sentence makes sense by clicking either *True* or *False*. At the end of a series of two to five sentence-letter sets, they recall the sequence of letters. Individuals are tested on three series of each length, 12 in total.

RSPAN scores are calculated based on the total number of letters recalled in order on any trial, regardless of whether the entire sequence of letters was correct. This partial-credit scoring shows high internal consistency and reduces skew (Conway et al., 2005).

Participants performed within the normative range for the RSPAN task ($M = 59.59$, $SD = 13$, Range = 19–75), but slightly higher than reported in a recent latent-variable analysis ($M = 51.60$; Unsworth et al., 2009). RSPAN scores did not differ as a function of gender $t(71) = .19$, $p = .49$.[2]

Math-anxiety. Math-anxiety was assessed using the short Math-anxiety Rating Scale (sMARS). The sMARS (Alexander & Martray, 1989) measures an individual's level of anxiety concerning math related situations. Across 25 items, participants rate how anxious they would be during math activities (e.g., "Listening to another student explain a math formula") on a 1–5 scale. The sMARS is a shortened version of the 98-item MARS (Richardson & Suinn, 1972). It is highly correlated with the original MARS ($r = .96$) and exhibits acceptable test–retest reliability. The mean sMARS score was 32.16 ($SD = 17.29$), slightly lower than that reported in Ashcraft & Kirk (2001; $M = 36.3$, $SD = 16.3$). Math-anxiety did not differ as a function of gender, $t(71) = .03$, $p = .98$.

Modular arithmetic. MA problems were always of the form "x ≡ y(mod z)". The left two operands were selected from numbers 2–98, with the constraint that the first number (x) was always greater than the second number (y). The mod operand (z) ranged from 2–9. Studies of mental arithmetic have determined that problems which involve the maintenance of information online, such as a carry operation, place particular demand on WM (DeStefano & LeFevre, 2004). In contrast, certain problems lend themselves to solution via heuristics (e.g., "mod 2" problems which are always false when the subtraction result is odd). These heuristic solutions make few demands on WM (DeCaro, Wieth, & Beilock, 2007). Based on these factors, problems in the math task were divided into Low and High demand categories corresponding to their relative recruitment of WM capacity. High Demand problems always included a carry operation during the subtraction step and could not be solved via simple heuristic. Low Demand problems did not have a carry step or could be solved using heuristics (e.g., mod 2 problems with an odd subtraction or mod 5 problems because they could be solved with the simple heuristic that only subtractions ending in 0 or 5 were true).

Participants completed 30 practice trials, followed by three experimental blocks of 70 problems, each separated by about a minute rest. The critical trials consisted of 54 High-Demand problems, in addition to 186 Low-Demand problems. This proportion of problems was selected such that participants were not overtaxed by difficult problems, but had enough time on task for the sluggish cortisol response to emerge. Order of blocks was counterbalanced across participants.

Procedure

Sessions were scheduled between 11:00 a.m. and 3:00 p.m. to minimize circadian variation in cortisol concentrations across participants. In order to collect proper measurements of salivary cortisol, participants were instructed not to eat, drink, chew gum, or brush their teeth for two hours before the session. Participants were compensated for their involvement.

Participants began by signing informed consent. The first saliva sample was collected by having individuals spit into a 12 × 75 mm polypropylene tube, which was then capped (Fisher Science; IL, U.S.A.). Next, all individuals were seated at a computer and introduced to MA. Participants saw MA problems such as $71 \equiv 23 (\text{mod } 3)$ on the computer and were asked to judge whether each problem was true or false as quickly and accurately as possible. Each trial began with a 500-ms fixation point, screen-center. This was replaced by a MA problem that remained on the screen until the participant responded. After response, the word "*Correct*" (in black) or "*Incorrect*" (in red) appeared for 1,000 ms, providing feedback. The screen then went blank for a 1,000-ms intertrial interval.

After the MA task, a second saliva sample was obtained from participants. This second sample was taken approximately 30 minutes after starting the math task, based on prior research establishing that salivary cortisol peaks between 21 and 40 minutes following stressor onset (Dickerson & Kemeny, 2004). Following the second saliva sample, participants completed the WM tasks. Last, participants filled out a short packet of questionnaires, including sMARS. After the experiment, saliva samples were kept frozen in the testing room for 2–3 weeks until transport to the lab, where they were stored until assayed. Samples were assayed in duplicate with ^{125}I-cortisol Corticote® radioimmunoassay kits (MP Biomedicals, CA U.S.A.) and reassayed if the CV was >20%. The sensitivity of the assay is 0.07 μg/dL.

Results

Only individuals whose average MA accuracy and cortisol concentration were within ± 2 *SD* of the mean of the group were included in the analyses. This resulted in the removal of four participants due to accuracy and three participants based on cortisol concentration. Sixty-six participants were retained in the analyses below.

[1] Self-report data concerning smoking behavior was also collected, however due to experimenter error this data was only collected for 42 subjects. Nonetheless, smoking behavior did not correlate with math-anxiety, WM, or salivary cortisol. Thus it was not included in further analysis.

[2] We also collected Operation Span (OSPAN), a measure of WM that incorporates math processing. For the purposes of studying the relation of WM and math-anxiety, OSPAN was not included due to its necessary relation to math processing.

Modular Arithmetic Accuracy

Overall, participants were fairly accurate on the MA problems ($M = 90\%$ correct, $SD = 6\%$) and completed the problems in about four seconds on average ($M = 3981$ ms, $SD = 1300$). As expected, the High-Demand problems were performed slower ($M = 6289$ ms, $SD = 2218$) and less accurately ($M = 81\%$, $SD = 12\%$) than Low-Demand problems ($M = 3232$ ms, $SD = 1126$; $M = 92\%$, $SD = 8\%$), $t(65) = 17.42$, $p < .0001$; $t(65) = -10.40$, $p < .0001$.

To explore how math-anxiety, individual differences in WM, and salivary cortisol related to low and high-demand problem performance, we began by regressing both low and high-demand math accuracy separately on math-anxiety, WM, post-MA cortisol (log transformed to reduce skew) and their interactions.[3] The regression approach is preferable to performing a median split and dichotomizing continuous variables because the latter approach reduces power (Cohen, 1983) and under certain conditions can increase the probability of a Type I error (Maxwell & Delaney, 1993). Following Cohen and Cohen (2003), we only considered regression coefficients as significant if the overall F-statistic was significant. This procedure protects against Type-I error inflation associated with testing multiple regression coefficients.

For each regression, the assumptions of normality, homogeneity and error independence were verified through inspection of the residuals and a normal q-q plot. Diagnostics of leverage, discrepancy and influence were also considered for each regression to confirm that the relationships were not the result of a few extreme or influential cases. DFBETA, a measure of the effect an individual observation has on a particular beta did not exceed the threshold of $\pm$ 1 (Cohen et al., 2003). Cook's Distance, a measure of the effect of a particular observation on overall fit, did not exceed one for any observation and no residual reached significance as a regression outlier using the Beckman and Cook (1983) procedure ($\alpha = .05$). No leverage values (h^*_{ii}) differed substantially from the distribution of values and only four observations (6%) were identified for further examination (about 5% are expected on average). Thus, there was no evidence for extreme or influential data in the regression. Last, we tested for multicollinearity using the variance inflation factor (VIF). A VIF of 10 is considered strong evidence for multicollinearity (see Cohen et al., 2003). No predictor VIF exceeded 1.7.

The regression equation predicting high-demand accuracy from math-anxiety, salivary cortisol, WM and their interactions was highly significant, $F(7, 58) = 3.10$, $p < .01$. High-demand MA accuracy was negatively related to overall math-anxiety, $\beta = -.493$, $t = -4.044$, $p < .001$. This main effect was qualified by the predicted three-way interaction between salivary cortisol, math-anxiety, and WM, $\beta = -.260$, $t = -2.15$, $p < .05$. The main effect for cortisol, WM and the two-way interactions did not reach significance (see Table 1). To fully understand the regression, we modeled one standard deviation above and below the mean for WM and math-anxiety. This simplifies interpretation by characterizing the data in terms of high and low WM and math-anxiety "groups" without actually breaking up the continuous variables (Aiken & West, 1991). The performance of these modeled groups on high-demand MA problems is plotted as a function of salivary cortisol concentration taken after MA in Figure 1.

As seen in Figure 1 (left panel), LWMs' math accuracy did not differ as a function of cortisol or math-anxiety. However, for HWMs, the relation between accuracy and cortisol concentration depended on their math-anxiety. For low math-anxious individuals, increasing cortisol was associated with better MA performance. The opposite pattern was found for individuals high in trait math-anxiety.

In terms of low-demand MA problems, the full regression model was not significant, $F(7, 58) = 1.42$, $p = .22$. Because these problems were specifically selected for their lesser reliance on WM, this nonsignificant result is an important control. If math-anxiety or cortisol predicted low-demand performance, this would suggest that these variables affect performance through another route apart from their effects on WM.

Modular Arithmetic Reaction Time

The same regressions performed on MA accuracy were also performed on MA RTs for the high and low-demand problems. Neither the full equation for high, $F(7, 58) = 1.54$, $p = .17$ nor low-demand, $F(7, 58) = 2.01$, $p = .07$ reached significance (see Table 1).

Discussion

In the current study we explored the relation between an individual's physiological response and their performance on a challenging math task. We predicted this relation would depend on whether a person was lower or higher in math-anxiety and thus their positive or negative construal of the math situation. We further suggested that this impact might be moderated by individual differences in WM. Our data showed strong support for these hypotheses. The relation between cortisol concentration (our measure of physiological response) and math performance depended on a participant's math-anxiety and their WM capacity.

For high math-anxious individuals, increasing cortisol concentrations lead to worse math performance. But, for low math-anxious individuals, this relationship was positive—increasing concentration of cortisol lead to higher performance. This pattern of results supports our claim that one's interpretation of the math situation helps to determine whether a physiological response will be disruptive or beneficial.

The effect of cortisol in this scenario was qualified by individual differences in WM capacity and the WM demands of the math problems performed. As predicted by previous research (Beilock & Carr, 2005), low-demand problems were not affected by the interaction of math-anxiety and cortisol. Moreover, because low working memory participants (LWMs) often do not rely heavily on WM to solve mathematical computations (Beilock & DeCaro, 2007), their performance remained unchanged with increasing concentrations of cortisol even on the high-demand problems. In contrast, high working memory participants' (HWMs) math accuracy was affected by an interaction between math-anxiety and

[3] As mentioned above, we collected cortisol prior to the math task to measure individual differences in baseline cortisol. For simplicity, this variable was not reported in the analysis. However, results remained significant when cortisol concentrations prior to the math task were included as a covariate.

Table 1
Regression Analyses for Modular Arithmetic Reaction Time and Accuracy

	High Demand		Low Demand	
	Accuracy	RT	Accuracy	RT
Predictor	β (*t*)	β (*t*)	β (*t*)	β (*t*)
sMARS	**−.49 (−4.04**)**	.11 (0.88)	−.34 (−2.60*)	.09 (0.66)
RSPAN	.09 (0.72)	−.06 (−0.43)	.16 (1.08)	−.05 (−0.34)
Cortisol	.18 (1.51)	−.18 (−1.39)	.06 (0.48)	−.27 (−2.15*)
Cortisol × sMARS	.17 (−1.46)	.14 (1.07)	−.02 (−0.18)	.19 (1.54)
sMARS × RSPAN	−.01 (−0.06)	−.01 (−0.34)	−.02 (−0.11)	.07 (0.50)
RSPAN × Cortisol	.11 (0.91)	.23 (1.76)	−.03 (−0.25)	.17 (1.37)
sMARS × RSPAN × Cortisol	**−.26 (−2.15*)**	−.20 (−1.50)	−.21 (−1.58)	−.20 (−1.56)
Adjusted R^2	**.19**	.07	.05	.07
F	**3.11****	1.54	1.42	2.01

Note. Adjusted R^2, adjusted coefficient of determination; β, standardized regression coefficient. Regression coefficients that exceed $\alpha = .05$ for both the overall *F* test and the individual *t* are indicated in bold along with their respective adjusted R^2 and *F* statistics.
* $p < .05$. ** $p < .01$.

salivary cortisol on high-demand problems. HWMs that were also high in math-anxiety tended to perform worse on the math task as cortisol concentrations increased across individuals. However, HWMs low in math-anxiety excelled on the math task as cortisol concentrations increased. These results suggest that, given the cognitive resources and the opportunity to interpret physiological arousal as a motivational cue, individuals in a challenging environment can push themselves to higher levels of performance. Participants did also exhibit a global difference in performance as a function of math-anxiety. This is consistent with claims that high math-anxious individuals possess less experience with math overall, contributing to poor performance in addition to their online affective response (Tobias, 1985).

This work relies on correlational data, thus we draw causal conclusion cautiously. For instance, placement of the math-anxiety measure after math performance allows the alternative hypothesis that math accuracy affected reported math-anxiety (instead of vice versa). This hypothesis is unlikely, however, because WM measures separated these two tasks by about 40 minutes. Further, sMARS is a trait math-anxiety measure, with questions that consider stable anxieties as opposed to one's current affective state. Last, an explanation which claims that performance affected reported math-anxiety cannot account for the WM component of our 3-way interaction (i.e., that HWMs, but not LWMs, show a relationship between performance and math-anxiety).

Second, it is also possible that cortisol concentrations might not affect performance, but instead may be a byproduct of performance outcomes. For instance, perhaps when low math-anxious individuals notice they are performing well, their cortisol concentrations increase; likewise, when high math-anxious individuals

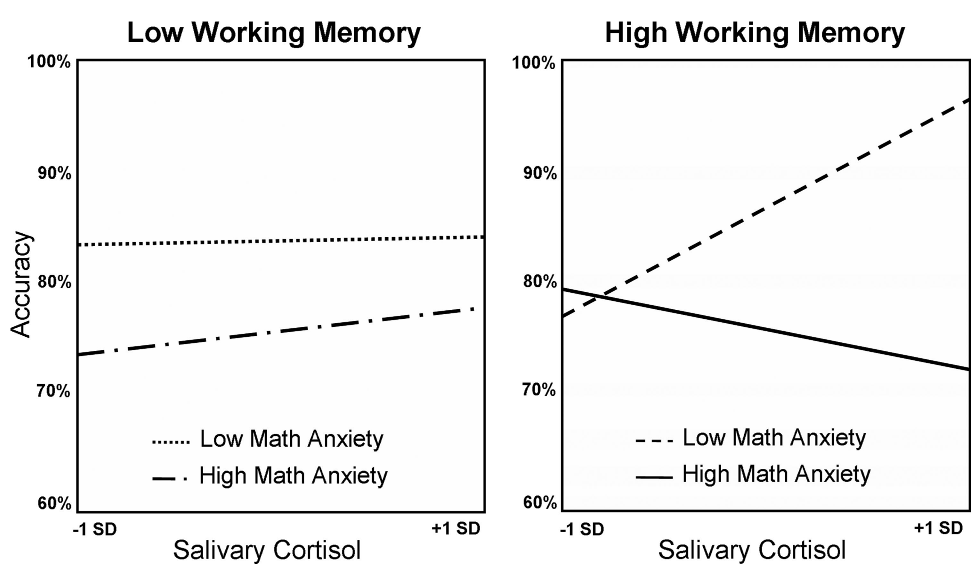

Figure 1. Mean modular arithmetic accuracy on high-demand problems as a function of WM, Math-anxiety and Cortisol.

notice they are making mistakes, their cortisol increases. However, a meta-analysis of cortisol studies points to uncontrollable situations which include potential social-evaluative stress as eliciting the strongest cortisol response (Dickerson & Kemeny, 2004). These criteria are consistent with failure on a difficult math task and thus could explain the experience and performance of highly math-anxious individuals, but not those lower in math-anxiety.

When considered in tandem with previous experimental manipulations of situation-induced anxiety (Beilock and DeCaro, 2007; Beilock & Carr, 2005 Dickerson & Kemeny, 2004), these data support the claim that anxiety affects performance through its impact on the WM system. The results also suggest that explicit measures of anxiety alone cannot account for the full impact of stress on performance. Physiological factors such as cortisol also play a role. In sum, the results suggest future avenues of research toward isolating a cognitively (Beilock & Carr, 2005) and biologically (Roozendaal et al., 2004) plausible mechanism for online math performance decrements related to anxiety.

Last, the essential role of affect in this ostensibly "cold" cognitive task is of special note. Math performance in adults is most often studied from a purely cognitive approach (Ashcraft, 1992; DeStefano & LeFevre, 2004), in which differences in affective processes are accepted as a necessary source of random variation. Yet, in the current study, the interaction of affective processes with cognitive ability account for 25% of the variance in accuracy. This argues strongly that a cold cognitive task such as math problem solving can only be understood through a theoretical lens that includes both affective and cognitive sides of the theoretical coin.

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