Title

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Do First Impressions Matter? How Problem Representation Shapes Performance in Complex Math Problem Solving

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Abstract

Initial perceptions of math problems are critical for performance; novices tend to fixate on surface structures, while experts look deeper towards strategies. However, it remains unclear how these early representations change across problem-solving phases and explain performance. In this study, 126 undergraduates solved 20 SAT-level math problems: 10 timed (90sec time-limit) and 10 untimed. For each problem, participants rated perceived calculation—a surface feature of problem representation—after brief (3sec) exposure and again after attempting the problem. Participants substantially overestimated calculation demand at first exposure and revised these judgments downward after solving (Cohen's d=0.84). Participants with lower problem-solving confidence showed even larger revisions (Cohen's d=0.61). Critically, only pre-solving perceived calculation demand predicted performance (partial r=-0.45), an effect primarily mediated by task-specific confidence (49.65% of the total effect). Math-anxiety also contributed explanatory power, particularly under time-pressure. Overall, effective problem-solving appears to rely on rapid, structure-based representations that guide strategy selection.

Keywords: mathematical problem-solving; problem representation; problem-solving confidence; metacognitive judgements; math anxiety; time pressure

Introduction

Solving complex problems is a foundational cognitive skill, central to success in mathematics, science, and many real-world domains. Mathematical problem solving, in particular, provides a well-defined context in which to study this skill, as problems are characterized by explicit goals, constraints, and solution spaces. Yet success in solving such problems may hinge not only on formal knowledge or strategy execution, but on how a problem is initially perceived. Research from studying the cognitive processes of experts and novices solving physics problems suggests that novices tend to focus on literal or surface features of the problem and that largely shapes their performance (Larkin et al., 1980; Chi et al. 1981). Similar patterns have been found for complex math problems (Schoenfeld and Herrmann, 1982). In the present study, we examine whether these early problem representations matter for complex mathematical problem solving by tracking how individuals' perceptions of calculation demand change from first exposure to post-solving reflection, and how those perceptions relate to performance on SAT-level math problems.

Cognitive Theory of Mathematical Problem Solving

Performance on complex mathematical problems varies widely even among individuals with similar levels of mathematical training. Across cognitive models of mathematical problem solving, there is broad agreement that the process of problem-solving unfolds across distinct phases, including understanding the problem, planning a strategy, executing a solution, and reviewing the outcome (Polya, 1957; Carlson and Bloom, 2005; J.R. Anderson et al. 2014). Despite this process-oriented view, empirical work has often focused on final accuracy or solution strategies, leaving open questions about how problem perceptions influence performance before, during and after problem-solving.

In the present study, we focus on two theoretically and empirically tractable phases of problem solving. We refer to the initial phase as Problem Representation, defined as the rapid formation of expectations and interpretations upon first encountering a problem. We refer to the final phase as Problem Review, defined as individuals' reflective assessment of the problem after attempting a solution. These phases broadly correspond to Polya's "understanding" and "looking back" stages and capture how perceptions evolve before and after engagement with complex problems (Polya, 1957).

Problem Perception and Expertise

Effective problem representation depends on how individuals perceive a problem's structure and demands. Schoenfeld and Herrmann demonstrated that expert and novice mathematical problem solvers differ systematically in their problem perceptions (1982). Novices tend to rely on surface features of problems (e.g., the presence of polynomials or specific symbols), whereas experts are more likely to perceive deep structural features that signal appropriate solution strategies. Importantly, Schoenfeld and Herrmann showed that changes in problem perception accompanied—and plausibly enabled—improvements in problem-solving proficiency.

One critical but understudied surface feature is perceived calculation demand—the extent to which a problem is expected to require calculation. We conceptualize perceived calculation demand as a metacognitive judgment about the computational resources a problem will require. This construct captures a form of problem perception that is rapid, intuitive, and actionable.

In G. Boleda, I. Dautriche, M. Maldonado, C. Saldana and T. Torrent (Eds.), *Proceedings of the 48th Annual Conference of the Cognitive Science Society*

Confidence, Self-Efficacy, and Math Anxiety

How people perceive problems is related to how they perceive their ability to solve problems. Research on mathematics performance has identified both self-efficacy—beliefs about one's ability to solve a given problem—and math anxiety as robust predictors of performance. Higher self-efficacy or confidence is associated with greater persistence, strategic flexibility, and metacognitive control, whereas math anxiety is associated with avoidance, intrusive worry, and reduced working memory availability (Živković et al., 2023; Ashcraft and Faus, 1994; Scheibe et al., 2023; Ramirez et al., 2016). Self-efficacy and math anxiety are distinct psychological constructs and contribute to problem-solving performance in unique ways (Lee, 2009). Math anxiety is engaged prior to problem-solving: high-math-anxious individuals show increased activation in pain and threat network areas in anticipation of doing math (Lyons and Beilock, 2012). The literature on problem-solving confidence, math anxiety, and performance has largely developed independently from phase-based models of problem solving, leaving open questions about when and how problem-solving confidence and anxiety exert their influence on the timeline of solving a problem.

In this study, we measured math anxiety at the trait level using the standard math anxiety scale. However, to understand how perceptions and metacognitive judgements relate to specific problem representations, we measured problem-solving confidence and perceived calculation demand at the task level (i.e., separately for each problem).

Time Pressure

Prior work has shown that performance on complex math problems decreases under time pressure, and math anxiety may interact with these performance deficits (Kellogg et al., 1999). To explain this effect on performance, multiple studies have demonstrated that time pressure overloads working memory, resulting in poorer problem-solving outcomes (Beilock et al., 2004; Beilock et al., 2005). In the context of complex math problems, time pressure appears to alter strategy selection by constraining the time available for planning and execution. Experimental manipulations of time pressure show that, in the absence of time constraints, individuals accumulate more information about a problem and use it to inform strategy selection and execution (Caviola et al., 2017). Given that mathematical problem-solving is often evaluated under time constraints and that time pressure can alter the problem-solving process, the present study examines how time pressure affects problem perception both before and after solving. Specifically, we ask whether having more time to engage with a problem leads to different calibration of problem perceptions across problem-solving phases.

The Present Study

In the present study, we examined how early perceptions of complex math problems change from before to after solving, and how these perceptions drive performance. We operationalized perception of complex math problems using a surface feature to build on expert-novice findings. We measured this through "perceived calculation demand", which we define as a metacognitive judgment about the amount of calculation a problem is expected to—or did—require. Importantly, we measured this perception at two distinct phases: immediately after a brief initial exposure to a problem (pre-solving) and again after attempting to solve the problem (post-solving). This corresponds to the Problem Representation and Problem Review phases of complex problem-solving, respectively. This design allowed us to examine both the stability of problem perceptions and the degree to which individuals recalibrate their judgments across the problem-solving process. Additionally, we included a time pressure manipulation to test whether pre- and post- solving problem perception changes as a result of time allotted on a problem.

Using real-world complex math problems designed for the SAT (online SAT practice problems), we examined whether early perceptions of calculation demand (pre-solving) predict performance more strongly than post-solving perceptions, and whether this relationship is mediated by task-specific problem-solving confidence and math anxiety. Building on prior work on expert–novice differences in problem perception, we propose that individuals whose early assessments require little revision after problem-solving exhibit more expert-like representations and successful performance.

The current study addresses the following questions:

- RQ 1a: How does perceived calculation demand change from initial exposure to post-solution evaluation after solving complex math problems?
- RQ 1b: Does task-specific confidence moderate the calibration of perceived calculation demand from pre- to post-solution?
- RQ 1c: Does problem-solving under time pressure alter the relationship between pre- and post- solution perceived calculation demand?
- RQ 2a: Which phase-specific perception of calculation demand best predicts performance on complex math problems?
- RQ 2b: To what extent do problem-solving confidence and math anxiety mediate the relationship between early perceived calculation demand and performance?
- RQ 2c: How does the condition of time pressure interact with perceived calculation demand predicting performance?

Methods

Participants

A total of 126 undergraduate students from Georgetown University participated in the study. Five participants were excluded: three for failing attention checks and two for insufficient retained trials (see Data Pruning), yielding a final sample of 121 participants. Participants received course credit

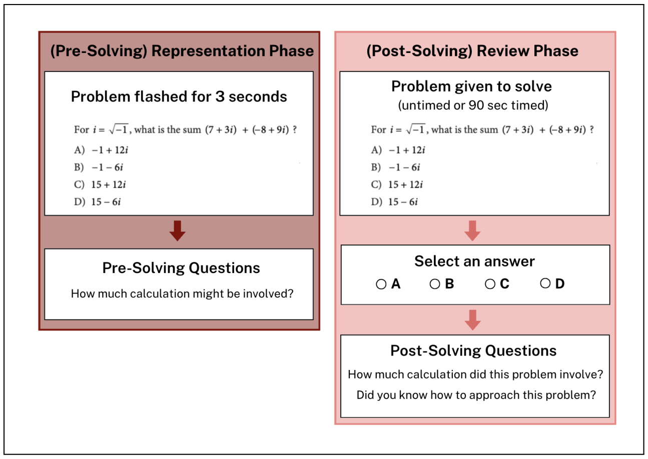

Figure 1: Task Design For Pre- and Post-Solving Phases

or monetary compensation for their participation. All procedures were approved by the university's institutional review board.

Materials

The stimulus set consisted of 20 SAT-level mathematics problems drawn from publicly available SAT practice materials. Problems spanned algebra, geometry, and word problem formats and were selected to reflect the range of conceptual and computational demands typical of high-stakes standardized testing. SAT-level problems were chosen to provide ecologically valid examples of complex math problems that are familiar in structure but nontrivial in execution for undergraduate participants.

Procedure

The study was administered in-lab using Qualtrics and consisted of two main sections followed by post-task questionnaires. Section 1 consisted of 10 SAT-level problems, with untimed problem-solving. Section 2 included a different set of 10 SAT-level problems, with a 90 second time limit on problem-solving. Each section included two phases: the pre-solving representation phase and the post-solving review phase, allowing perceptions of calculation demand to be measured both before and after engagement with each problem. In each section, participants first rated all 10 problems (in a randomized order), then solved those corresponding 10 problems.

(Pre-Solving) Representation Phase In the problem representation phase, prior to solving, participants were shown a math problem for 3 seconds, a duration chosen to capture rapid, pre-analytic impressions before participants could begin solving the problem. Following this brief exposure, participants responded to questions about their initial perceptions of each problem. Measures from this phase are referred to as "pre-solving".

1. How much calculation might be involved?
2. How helpful would a calculator be?

(Post-Solving) Review Phase

In the post-solving review phase, participants solved and answered math problems. Afterwards, they completed a set of questions assessing their perceptions and experience. The measures from this phase are referred to as "post-solving".

1. How much calculation did this problem involve?
2. Did you know how to approach this problem? (yes/no)
3. Did you guess? (yes/no)

Participants completed one practice problem before beginning the trials. In Section 1, problems were untimed, allowing participants to work at their own pace. In Section 2, a 90-second time limit was imposed on each problem to examine whether time pressure altered perception–performance relationships. Across the full study, participants completed ratings and solutions for a total of 20 unique SAT math problems (10 per section), with problem order randomized across participants. No feedback on accuracy was provided at any point.

Post-Task Questionnaires After completing both sections, participants filled out a battery of questionnaires assessing individual differences in affect, beliefs, and experience, including Math anxiety (shortened Math Anxiety Rating Scale; sMARS) and Demographics. Questionnaire order (besides demographics which was always presented as the final questionnaire) was randomized across participants.

Data Pruning

Of the 123 participants who passed attention checks, 37 trials (3% of untimed trials) were excluded due to unusually long response times, defined as responses exceeding a pre-specified upper threshold indicative of disengagement. Participants with fewer than 16 retained trials in the untimed condition were excluded entirely (n = 2). The final dataset consisted of 1173 trials from 121 participants.

Measures

All key variables were aggregated at the participant level unless otherwise specified and z-score standardized prior to analysis.

Math Anxiety Math anxiety was measured using the shortened Math Anxiety Rating Scale (sMARS) (Alexander & Martray, 1989). Scores were computed according to standard scoring procedures, with higher values indicating greater math anxiety.

Performance Performance was defined as the proportion of correctly solved problems out of the total number of retained trials per participant. Participants were required to have at least 16 retained trials (out of 20 total) to be included in performance analyses.

(Pre-Solving) Perceived Calculation Demand Participants rated how much calculation (0–100 scale) they believed would be involved in each problem. Ratings were averaged across all trials for each participant. This measure captures participants' initial expectations about computational demands prior to engaging with the problem.

(Post-Solving) Perceived Calculation Demand Participants rated how much calculation (0–100 scale) the problem actually involved after attempting and answering the problems. Ratings were averaged across all retained calculation trials and standardized. This measure reflects retrospective assessment of computational demand following problem solving.

Task-Specific confidence Problem-solving confidence was measured on the task level with the question "Did you know how to approach this problem?" Responses were coded as 1 (yes) or 0 (no). For each participant, problem-solving confidence was operationalized as the proportion of problems to which they responded "yes" to. This measure reflects participants' perceived strategic competence across tasks.

Reported Guessing After attempting to solve and answer the problem, participants' responded to the question "Did you guess?" These responses were coded as 1 (yes) or 0 (no). This was measured as the proportion of problems to which participants responded "yes" to.

Results

Analyses were conducted at the participant level using z-scored coefficients unless otherwise noted. All reported tests were two-tailed. To report effect sizes, comparisons of means use Cohen's d and regression coefficients use partial r values.

Research Question 1a: How does perceived calculation demand change from initial exposure to post-solution evaluation after solving complex math problems?

To examine how perceived calculation demand changed across phases of problem solving, we compared participants' ratings during problem representation (pre-solving) and review (post-solving) phases. On average, participants rated calculation demand higher pre-solving ($M = 28.33$, $SD = 13.93$) than post-solving ($M = 18.39$, $SD = 9.47$). This difference was significant ($t = 6.52$, Cohen's $d = 0.84$, $p < 0.001$). Perceived calculation demand was moderately correlated across phases ($r = 0.54$, $p < 0.001$).

Research Question 1b: Does problem-solving confidence moderate the calibration of perceived calculation demand from pre- to post-solution?

We examined whether task-specific problem-solving confidence moderated changes in perceived calculation demand using a 2x2 mixed ANOVA. problem-solving confidence was grouped into high and low using a median split of the task-specific problem-solving confidence averaged across trials per participant. Perceived calculation rating was the dependent variable, phase of perceived calculation rating (pre- or post-solving) was the within subjects factor, and problem-solving confidence (high or low) was the between subjects factor. Results showed a main effect of problem-solving confidence ($F(1,121) = 9.92$, $p = 0.002$). Additionally, there was a main effect of phase ($F(1,121) = 90.96$, $p < .001$). The interaction was also significant ($F(1,121) = 6.71$, $p = 0.011$). Paired t-tests revealed that the differences between pre- and post-solving perceived calculation ratings were significant for the high problem-solving confidence group ($t = 5.58$, $p < 0.001$, Cohen's $d = 0.51$) and low problem-solving confidence group ($t = 6.72$, $p < .001$, Cohen's $d = 0.61$).

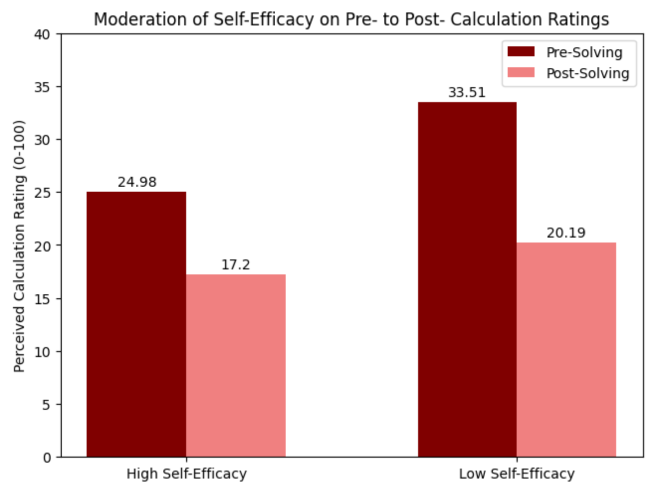

Figure 2: Moderation Effect of Problem-Solving Confidence on Perceived Calculation Demand Calibration

Research Question 1c: Does problem-solving under time pressure alter the relationship between pre- and post- solution perceived calculation demand?

Problem-solving under time pressure was associated with higher perceived calculation ratings before (timed: $M = 29.85$, $SD = 15.33$; untimed: $M = 26.90$, $SD = 14.66$) and after solving (timed: $M = 21.32$, $SD = 11.51$; untimed: $M = 15.46$, $SD = 9.34$). Participants reduced their perceived calculation ratings after solving in both the timed and untimed conditions. A 2 (Phase of calculation rating: pre vs. post) × 2 (Time pressure: timed vs. untimed) repeated-measures ANOVA revealed a significant interaction between the phase of measuring perceived calculation and the application of time pressure ($F(1, 121) = 5.34$, $p = 0.022$). Paired t-tests showed that the difference between pre- and post- solving perceived calculation ratings was significant during the timed trials ($t = 4.93$, $p < 0.001$, Cohen's $d = 0.63$), as well as during the untimed trials ($t= 7.30$, $p < 0.001$, Cohen's $d = 0.93$).

To examine whether time pressure and problem-solving confidence interacted in predicting changes in perceived calculation ratings, we used a mixed-effects linear model. The change in perceived calculation (post minus pre) was the dependent variable. Fixed effects included time pressure, task-specific problem-solving confidence (continuous), and their interaction. Random intercepts for participants accounted for individual differences in perceived calculation adjustments. Time pressure significantly predicted change in calculation ratings (b = 2.92, SE = 1.23, z = 2.37, p = 0.018). Task-specific problem-solving confidence was marginally associated with change (b = 2.06, SE = 1.19, z = 1.73, p = 0.084). Critically, the interaction between time pressure and problem-solving confidence was significant (b = 3.42, SE = 1.23, z = 2.77, p = 0.006), indicating that the effect of time pressure on adjusting perceived calculation ratings was greater for higher problem-solving confidence participants.

Research Question 2a: Which phase-specific perception of calculation demand best predicts performance on complex math problems?

We examined whether perceived calculation demand during problem representation (pre-solving) or review (post-solving) more strongly predicted performance on complex math problems. Higher pre-solving perceived calculation demand was strongly correlated with lower performance (r = 0.45, p < 0.001). Post-solving perceived calculation demand had a weaker negative relationship with performance (r = 0.24, p = 0.007).

To assess the unique predictive capacity of each measure, we used a multiple linear regression model to predict performance. Only pre-solving perceived calculation demand emerged as a significant predictor (partial r = 0.40, p < 0.001), whereas post-solving perceived calculation demand did not (partial r = 0.0077, p = 0.93). Together, the model accounted for 20.5% of variance in performance ($R^2 = 0.205$).

Research Question 2b: To what extent does problem-solving confidence mediate the relationship between early perceived calculation demand and performance?

To investigate mechanisms underlying the relationship between pre-solving perceived calculation demand and performance, we tested mediation models including task-specific problem-solving confidence and math anxiety as candidate mediators.

Task-specific problem-solving confidence was strongly negatively correlated with pre-solving perceived calculation demand (r = 0.35, p < 0.001) and positively correlated with performance (r = 0.68, p < 0.001). Math anxiety was positively correlated with pre-solving perceived calculation demand (r = 0.19, p = 0.038) and negatively correlated with performance (r = 0.40, p < 0.001).

In a combined mediation model, task-specific problem-solving confidence significantly mediated 41.5% of the total effect of pre-solving perceived calculation demand on performance (p < 0.001), while math anxiety accounted for an additional 8.15% (p = 0.044). Together, problem-solving confidence and math anxiety explained 49.65% of the total effect. Both mediators remained significant, indicating that they captured partially distinct mechanisms.

The two significant mediators together explained 49.65% of the total effect. The total effect in this model was -0.52 (95% CI [-0.71, -0.34]), direct effect was -0.29 (95% CI [-0.549514, -0.036]). The indirect effect for task-specific problem-solving confidence was -0.22 (95% CI [-0.36, -0.11]). The indirect effect for math anxiety was -0.043 (95% CI [-0.11, -0.0021]).

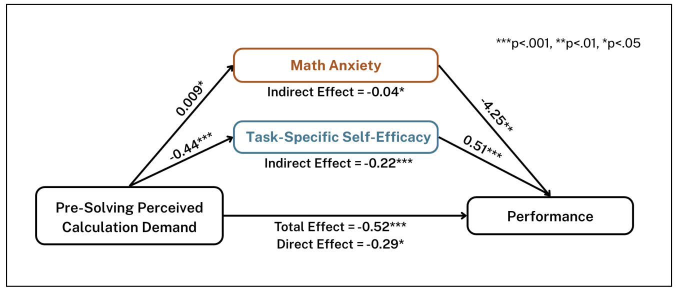

Figure 3: Mechanisms of Pre-Solving Perceived Calculation Predicting Performance

Research Question 2c: How does the condition of time pressure interact with perceived calculation demand predicting performance?

Time pressure decreased performance (t = 4.99, Cohen's d = -0.64, p < 0.001; timed M = 63.98, SD = 18.56; untimed M = 75.78, SD = 18.37). Additionally, participants reported guessing more under time pressure (t = -4.80, Cohen's d = -0.61, p < 0.001; timed M = 31.95, SD = 20.78; untimed M = 19.96, SD = 19.93).

Separate regression analyses for timed and untimed problems revealed consistent patterns. In both conditions, pre-solving perceived calculation demand was the only significant predictor of performance (untimed: partial r = -0.25, p = .005; timed: partial r = -0.31, p < 0.001), whereas post-solving perceived calculation demand did not predict accuracy in either condition (untimed: partial r = -0.12, p=0.19; timed: partial r = -0.032, p = 0.70).

Time pressure altered the mechanisms linking early perceptions to performance. problem-solving confidence's mediating role decreased from 48.73% (of the total effect) under untimed conditions (p = 0.048) to 27.14% under time pressure (p = 0.004). Conversely, math anxiety's role increased from a non-significant 7.14% (p = 0.18) to a significant 11.72% (p = 0.048), emerging as a mediator only under time pressure.

Discussion

The present study demonstrates that problem representation is a critical phase of mathematical problem-solving. Individuals' initial perceptions of how calculation-intensive a problem will be—formed within seconds of first exposure—explain performance more strongly than perceptions formed after completing the problem. These findings show that early perceptions shape downstream problem-solving success.

problem-solving confidence and the Stability of Problem Representations

A key contribution is the demonstration that task-specific problem-solving confidence moderates how stable problem representations remain across the problem-solving process. Participants with higher problem-solving confidence showed strong correspondence between pre- and post-solving judgments of calculation demand, indicating relatively stable and well-calibrated representations. In contrast, participants with lower problem-solving confidence exhibited greater recalibration after solving the problem, suggesting that their initial representations were more susceptible to change due to overreliance on surface features.

This pattern closely mirrors classic expert–novice distinctions in mathematical cognition. It has been shown that experts tend to rapidly encode deep structural properties of problems that support efficient planning, whereas novices rely more heavily on surface features and must revise their understanding (Larkin et al., 1980; Chi et al. 1981; Schoenfeld and Herrmann, 1982). Although expertise was not directly manipulated in the present study, performance across the SAT problems served to distinguish effective and ineffective problem-solvers. Considering how problem-solving confidence and performance interacted, higher task-specific problem-solving confidence was associated with representations that were formed early, remain stable, and guide more successful solution attempts.

Mechanisms Linking Early Problem Representation to Performance

Mediation analyses further clarified how early problem representations influence performance. Task-specific confidence emerged as the primary pathway through which perceived calculation demand affected accuracy. Participants who initially perceived a problem as calculation-intensive were substantially less likely to report knowing how to approach the problem, and this perceived lack of strategic access accounted for a large proportion of their performance deficit. Importantly, this effect persisted even when math anxiety was included in the model, indicating that early representations impair performance not solely by inducing negative affect, but by disrupting the formation of a viable plan.

Time Pressure

Time pressure reliably impaired problem-solving on SAT-level math problems; participants performed worse and reported more guessing under time pressure. Time pressure also elevated perceived calculation demand both before and after solving and reduced the degree to which participants revised their initial estimates. Crucially, time pressure altered the mechanisms linking early problem representations to performance. Without time constraints, the primary mechanism is metacognitive — individuals who overestimate calculation initially fail to identify effective strategies to solve the problems (problem-solving confidence). Under time pressure however, affective factors (math anxiety) significantly explain how initial perceptions impact performance. These findings suggest that under time pressure, individuals are less able to revise early, surface-based impressions of complex math problems into structure-based representations that support effective strategy selection (Caviola et al., 2017). This pattern is consistent with working memory overload accounts (Beilock et al., 2004; Beilock et al., 2005): reduced cognitive resources constrain both the ability to generate alternative representations and to regulate anxiety-related intrusions.

Limitations and Future Directions

Several limitations point to directions for future research. First, the present study focused exclusively on perceived calculation demand as a measure of initial problem representation. Although this dimension proved highly informative, future work should examine additional aspects of problem representation, such as perceived conceptual structure, familiarity, or strategies. Second, incorporating cognitive process measures would help clarify how early representations translate into specific solution behaviors.

Conclusion

This study shows that success in complex mathematical problem-solving is strongly shaped by initial problem representations formed within seconds of first exposure. Whereas much prior work has examined problem perception either before or after problem solving, the present study shows that change in perception across phases carries important information. Early perceived calculation demand predicted performance more strongly than post-solving perceptions. The ability to make accurate initial judgments that little subsequent revision appears to be a hallmark of effective problem solvers. Task-specific confidence was the primary mechanism linking early perceived calculation demand to performance, reflecting whether solvers identified a viable strategy early on. Math anxiety did not independently explain this relationship under no time pressure, but became a significant mediator when time pressure was imposed, suggesting that the imposition of time pressure shifts how early problem representations impact performance. Overall, effective problem solving appears to depend on forming accurate, stable representations from first impressions.

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