

# THE COMPENSATORY ROLE OF STRATEGY TRAINING ON SCIENCE KNOWLEDGE IN A GAME-BASED LEARNING ENVIRONMENT

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## Abstract

This study examined the effects of metacognitive strategy training on fifth-grade students' science knowledge and metacognitive monitoring within MISSIONS WITH MONTY, a game-based learning environment (GBLE) integrating science content, reading, and problem-solving. Participants were N = 129 fifth graders who engaged with the game in two conditions: a treatment group that received Training Camp, an explicit metacognitive training module, and a comparison group that played without training, over the course of six weeks. Results showed that Training Camp improved students' monitoring accuracy overall and moderated the effects of limited prior science knowledge. For low prior knowledge students, Training Camp yielded substantial gains in science knowledge ( $g = 0.87$ ), improved calibration ( $g = 0.88$ ), and reduced bias ( $g = 1.07$ ) compared to peers without training. Findings highlight the value of embedding metacognitive strategy support in serious games as a scalable way to promote both knowledge development and self-regulated reading practice.

Keywords: Metacognitive strategy training, Game-based learning environment, Science knowledge, Self-regulated learning, Metacognitive monitoring, Reading comprehension.

## 1 INTRODUCTION

The goals of scientific literacy center on helping individuals understand the complexities of the world and their role within it [1]. A strong foundation in science enables civic participation, informed decision-making, and lifelong learning, and recent research highlights the role of early science education in supporting literacy development, as prior knowledge shapes how readers interpret and retain new information [2] [3] [4]. In response, educators have turned to integrating science and literacy instruction, yet supporting students with limited prior knowledge remains a challenge. Training students to monitor their learning with greater accuracy has been shown to improve comprehension and performance [5] [6] [7] [8] [9] but such approaches are rarely adopted due to the resources and training they demand. Emerging technologies, such as game-based learning environments (GBLEs), may address these barriers by providing scalable, interactive, and feedback-rich supports for knowledge-building and reading comprehension.

### 1.1 The Role of Prior Knowledge in Reading Comprehension

Reading comprehension is a complex, dynamic process shaped by prior knowledge, defined as the learner's current understanding of a particular topic before encountering new information [10] [11]. It shapes comprehension by helping readers activate and organize new information into existing schema [12] [13]. However, readers with limited prior knowledge often struggle to build coherence as they must devote cognitive resources to constructing a framework of understanding, which can overtax an already limited working memory [11] [14].

Although prior knowledge may limit readers' ability to engage with text, it is not a fixed limiting factor. Prior knowledge is shaped by experiences and interest, and comprehension improves as learners develop conceptual understanding within knowledge domains [15] [16]. As readers encounter new information, related concepts are activated from memory, but strategic processes are needed to integrate relevant knowledge [17]. Contemporary comprehension models emphasize the importance of prior knowledge in comprehension [18] [19] but often lack practical guidance on how to support comprehension in real time or through coordinated instructional supports [20].

In response to the growing recognition that comprehension difficulties often stem from knowledge gaps, instructional models have increasingly emphasized integration of literacy and content instruction. Rather than viewing reading and content learning as sequential, content-integrated approaches embed literacy instruction within thematic, concept-rich domains of science and social studies [21] [22] [23]. Recent studies have shown success with accelerating vocabulary growth, conceptual development, and overall reading comprehension [24] [25] [27].

However, knowledge alone may not be sufficient for successful comprehension. Research consistently demonstrates that students benefit from explicit instruction in strategies that support monitoring and regulation of understanding, particularly when embedded in authentic contexts [28] [29]. Metacognitive strategy instruction interventions have improved students' metacognitive skills, leading to gains in comprehension and vocabulary [9]. These findings suggest that coupling content integration with metacognitive strategy may be especially beneficial for readers navigating complex informational texts.

## 1.2 The Compensatory Role of SRL and Metacognition

Self-regulated learning (SRL) refers to learners' active management of cognitive, motivational, and behavioral processes to achieve goals [30] [31]. Central to SRL is metacognition, the ability to monitor and regulate one's own thinking, playing a critical role in reading comprehension and academic success [32] [33]. In reading, metacognition involves both awareness of one's cognitive processes and how to regulate them strategically [34]. Widely recognized as the key to effective reading comprehension, struggling readers often lack the metacognitive awareness to recognize comprehension breakdowns and the strategic knowledge to monitor and repair their understanding, contributing to difficulties in reading comprehension [35] [36].

Metacognitive monitoring refers to the extent to which an individual's judgment about their performance aligns with their actual outcomes [37]. An increasing number of studies indicate that metacognitive monitoring accuracy interventions enhance students' ability to assess their own understanding and are often associated with improved academic performance [38] [9] [7] [46]. Metacognitive monitoring is often measured using calibration, or the absolute difference between confidence judgments and actual performance, and bias, which reflects tendencies toward over- or underconfidence [6] [38] [39] [37].

### 1.2.1 Promoting SRL and Metacognition in GBLEs

As educators have explored innovative ways to use technology to support student learning, GBLEs are uniquely positioned to promote deep engagement and support learning by simulating low-risk, exploratory spaces where learners can try out strategies, behaviors, and ideas without fear of failure [40]. These environments often require metacognitive skills, such as planning, monitoring progress, and adjusting strategies in response to changing game demands [40]. GBLEs like MISSIONS WITH MONTY have demonstrated benefits for science knowledge and metacognitive monitoring [41] as well as gains in reading motivation and comprehension [42]. However, few GBLEs have explicitly targeted the teaching of metacognitive reading strategies needed for constructing disciplinary knowledge. The current study addresses this gap by examining the role of a metacognitive strategy Training Camp embedded within the MISSIONS WITH MONTY game design. This study addressed the following research questions:

*Research Question 1: What is the impact of the metacognition strategy Training Camp on students' science knowledge, calibration, and bias in a GBLE?*

*Research Question 2: How does the metacognitive strategy Training Camp influence the effect of limited prior science knowledge on students' science knowledge, calibration, and bias in a GBLE?*

## 2 METHODOLOGY

### 2.1 Participants

Fifth-grade students from five public schools in North Carolina, participated as part of regular classroom instruction. They were randomly assigned to one of two conditions: Training Camp (n = 73) or No Training Camp (n = 56).

## 2.2 Materials and Procedure

This study used MISSIONS WITH MONTY, a digital GBLE in which students take on the role of young scientists investigating an animal disease outbreak. The game narrative follows Monty, a renowned monitor lizard scientist who has gone missing, and the closure of Wildlife University due to animal illness. To progress, players interact with researchers and read informational texts to solve the mysteries (Figure 1). Students played MISSIONS WITH MONTY twice weekly for 45 minutes over six weeks, navigating the game individually with teacher support limited to technical issues. The experimental manipulation involved the five-part, pre-game Training Camp module that provided explicit instruction in metacognitive strategies, including gist identification and monitoring accuracy. Only students in the treatment group participated in the Training Camp.

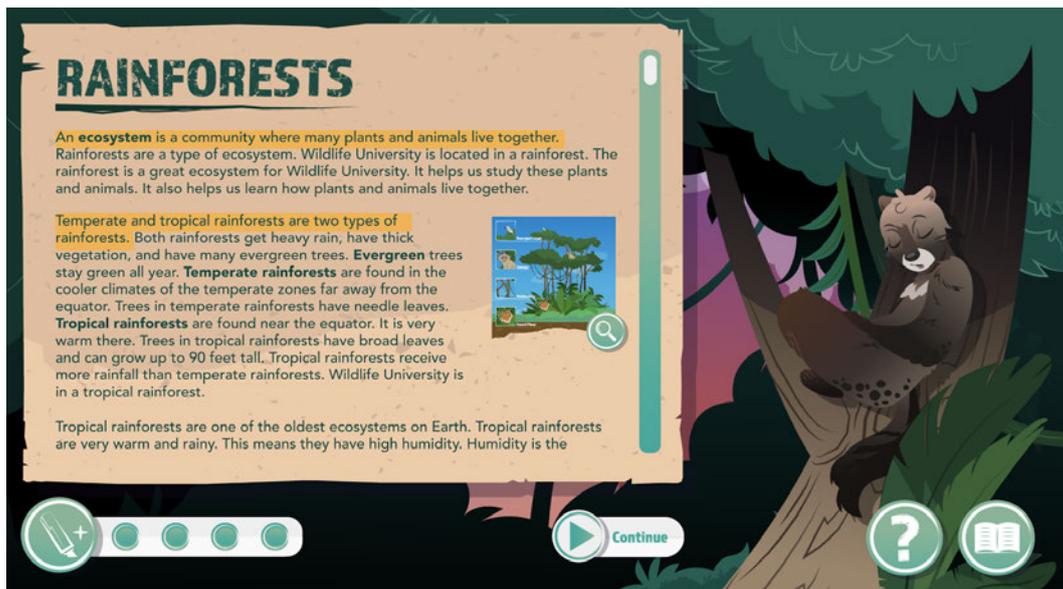


Figure 1 MISSIONS WITH MONTY example reading passage

After each reading, participants completed multiple-choice items in the game's Knowledge Challenges. They then rated their confidence on a 100-point scale using a rainforest vine-themed slider (Figure 2). All students completed pre- and post-tests assessing science knowledge. The 20-item scale demonstrated acceptable internal consistency ( $\alpha = .68$  pretest,  $.83$  post-test).



Figure 2 MISSIONS WITH MONTY confidence judgment rating system

### 3 RESULTS

Prior to analysis, the dataset was screened for accuracy, missing data, and outliers. All continuous variables were inspected for normality, skewness, and kurtosis using descriptive statistics and histograms. While calibration showed skewness, no transformations were applied in order to preserve interpretability, especially given that calibration and bias are both accuracy metrics. Categorical variables were dummy coded for analysis. Although the initial analytic plan included multilevel modeling (MLM), intraclass correlation coefficients (ICCs) were near zero for 3 of the 4 outcome models, indicating minimal clustering at the teacher level. Additionally, with only 10 teacher clusters, MLM was underpowered and potentially unstable (McNeish & Stapleton, 2016). Therefore, final analyses were conducted using single-level regression models, focusing on student-level predictors and interactions.

#### 3.1 Descriptive Statistics

Table 1 presents the means and standard deviations for all outcome variables, organized by treatment group. Inferential statistical analyses are presented in the following section to determine the impact of strategy training in the treatment condition.

*Table 1 Descriptive statistics - means and standard deviations by treatment group*

	<b>No (N = 56)</b>		<b>Training Camp (N = 73)</b>	
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
<b><i>General Science Knowledge Pre-Test</i></b>	10.50	3.20	11.64	3.37
<b><i>General Science Knowledge Post-Test</i></b>	11.33	3.99	13.15	5.02
<b><i>Calibration Pre-Test</i></b>	0.25	0.08	0.23	0.08
<b><i>Calibration Post-Test</i></b>	0.29	0.14	0.17	0.01
<b><i>Bias Pre-Test</i></b>	0.08	0.20	0.04	0.19
<b><i>Bias Post-Test</i></b>	0.20	0.23	0.10	0.14
<b><i>Self-Efficacy Pre-Test</i></b>	5.07	1.38	5.23	1.23
<b><i>Self-Efficacy Post-Test</i></b>	4.68	1.61	5.44	1.48

#### 3.2 Research Question 1: What is the impact of metacognition strategy training camp on students' science knowledge, metacognitive calibration, and metacognitive bias?

Separate multiple regression analyses were conducted for each dependent measure. For each analysis, predictor variables included condition (Training Camp vs. no Training Camp) and a pre-study measure of the targeted outcome measure. Pre-test scores were included as covariates to control for baseline differences across conditions. Results are presented separately by outcome measure below.

##### 3.2.1 Science Knowledge

The multivariate regression analysis revealed that the model was significant (Table 2). Science prior knowledge predicted post-game science knowledge, ( $\beta = 0.64, p < 0.001$ ). Training Camp was not a significant predictor ( $\beta = 0.92, p < .01$ ).

##### 3.2.2 Metacognitive Calibration

The multivariate regression analysis for calibration was significant (Table 3). Both initial metacognitive calibration ( $\beta = 0.53, p < .01$ ) and Training Camp, ( $\beta = -0.10, p < .001$ ) were significant predictors of post-treatment calibration.

##### 3.2.3 Metacognitive Bias

The multivariate regression analysis for bias was significant (Table 4). Both initial metacognitive bias, ( $\beta = 0.48, p < 0.001$ ) and Training Camp, ( $\beta = -0.10, p < .01$ ) were significant predictors of post-treatment metacognitive bias, ( $\beta = -0.10, p < .01$ ).

### 3.3 Research Question 2: To what extent does Training Camp moderate the relationship between prior science knowledge and students' outcomes in science knowledge, calibration, and metacognitive bias?

Students were categorized as low prior science knowledge using a median split on the pretest. This approach ensured balanced group sizes and statistical rigor given the low skew and variability, and no correlation with condition ( $r = 0.17$ ) [43].

#### 3.3.1 Science Knowledge

A linear regression examined the effects of strategy training, prior science knowledge, and their interaction on post-intervention science knowledge (Table 2). Predictors included students' pre-intervention science knowledge scores, Training Camp participation, prior science knowledge level (low vs. high), and the Training Camp and prior science knowledge group interaction. The overall model was significant, ( $F(4, 82) = 13.17, p < .001$ ), explaining approximately 29% of the variance in post-intervention scores ( $R^2 = .29$ ). The main effects were not statistically significant but a significant interaction between Training Camp and prior science knowledge emerged ( $\beta_4 = 0.88, p < 0.05$ ).

Table 2 Regression coefficients for the prediction of post-intervention science knowledge (standardized)

	Model 1	Model II
Science Knowledge Pre-Test	0.47*** (0.09)	0.49** (0.17)
Training Camp	0.18 (0.87)	-0.23 (0.22)
Low Prior Science Knowledge		-0.42 (0.31)
Training Camp x Low Prior Science Knowledge		0.88* (0.36)
Intercept	-0.07 (0.10)	0.16 (0.16)
	$N = 87$	$N = 87$
	$R^2 = 0.24$	$R^2 = 0.29$

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

The effect of prior knowledge on post-intervention science knowledge was moderated by participation in Training Camp. In the control group, students with low prior science knowledge scored 0.42 standard deviations lower than their peers with higher prior science knowledge. In contrast, among students who completed Training Camp, those with low prior science knowledge scored 0.46 standard deviations higher than their high-science knowledge peers. Probing the interaction further revealed that, for students who began the intervention with low prior knowledge, participation in Training Camp was associated with 0.65 standard deviations increase in post-intervention science knowledge compared to similar peers who did not receive the intervention. The effect size for this interaction was large ( $g = 0.87$ ), suggesting the Training Camp had a meaningful benefit for students with low prior knowledge.

#### 3.3.2 Calibration

A linear regression was conducted to examine the effects of strategy training, low prior science knowledge, and their interaction on post-intervention calibration (Table 3). Predictors included students' pre-intervention calibration scores, Training Camp participation, low prior science knowledge, and the interaction between Training Camp and low prior knowledge. The overall model was significant, ( $F(4, 82) = 7.61, p < .001$ ), explaining approximately 38% of the variance in post-calibration scores ( $R^2 = .38$ ). The main effects were statistically significant as well as the interaction between Training Camp and low prior knowledge ( $\beta_4 = -0.1, p < 0.05$ ).

Table 3 Regression coefficients for the prediction of post-intervention calibration

	<i>Model 1</i>	<i>Model II</i>
Calibration Pre-Test	0.53*** (0.17)	0.41* (0.16)
Training Camp	-0.10*** (0.02)	-0.05* (0.02)
Low Prior Science Knowledge		0.12** (0.04)
Training Camp x Low Prior Science Knowledge		-0.10* (0.45)
Intercept	0.15*** (0.04)	0.11** (0.04)
	<i>N</i> = 87	<i>N</i> = 87
	<i>R</i> <sup>2</sup> = 0.24	<i>R</i> <sup>2</sup> = 0.38

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

The effect of prior knowledge on post-intervention calibration was moderated by participation in Training Camp. Among students who received Training Camp, those with low prior science knowledge were only 0.02 units less calibrated than their higher-knowledge peers, effectively eliminating the calibration gap. In contrast, low-knowledge students in the control group were 0.12 units less calibrated than their peers. Among students with low prior knowledge, those who received Training Camp were 0.15 units closer to perfect calibration than those in the control group. The effect size was large ( $g = 0.88$ ), indicating a substantial improvement in metacognitive accuracy.

### 3.3.3 Bias

A linear regression was conducted to examine the effects of strategy training, low prior science knowledge, and their interaction on post-intervention calibration (Table 4). Predictors included students' pre-intervention bias scores, Training Camp participation, low prior science knowledge, and the interaction between Training Camp and low prior knowledge. The overall model was significant, ( $F(4, 82) = 7.61, p < .001$ ), explaining approximately 38% of the variance in post-calibration scores ( $R^2 = .38$ ). The main effects were statistically significant as well as the interaction between Training Camp and low prior knowledge ( $\beta_4 = -0.1, p < 0.05$ ).

Table 4 Regression coefficients for the prediction of post-intervention bias

	<i>Model 1</i>	<i>Model II</i>
Bias Pre-Test	0.48*** (0.10)	0.43*** (0.09)
Training Camp	-0.10*** (0.03)	-0.02 (0.04)
Low Prior Science Knowledge		0.11* (0.05)
Training Camp x Low Prior Science Knowledge		-0.16* (0.67)
Intercept	0.17*** (0.03)	0.11** (0.03)
	<i>N</i> = 87	<i>N</i> = 87
	<i>R</i> <sup>2</sup> = 0.35	<i>R</i> <sup>2</sup> = 0.39

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

A significant interaction indicated that the effect of prior knowledge on metacognitive bias was moderated by Training Camp participation. Model estimates indicated that among students with low prior science knowledge, those who completed Training Camp were 0.18 units less biased than those in the control group. In contrast, among students with higher prior knowledge, the effect of Training Camp on bias was minimal (-0.02), suggesting Training Camp was particularly effective in reducing overconfidence among students with low prior science knowledge. The relationship between prior knowledge and calibration bias also differed by treatment condition. In the control group, students with low prior knowledge were 0.11 units more biased than their peers. However, for the Training Camp condition, low-GSK students were slightly less biased than higher-knowledge students (-0.05), suggesting that the intervention may have reversed the typical overconfidence gap. The effect size for this interaction was very large ( $g = 1.07$ ), suggesting the Training Camp had a substantial benefit for students with low prior knowledge.

## 4 CONCLUSIONS

Science knowledge underpins literacy and lifelong learning [1] yet less is known about the processes that support its construction. This study tested Training Camp, a metacognitive strategy intervention embedded in the MISSIONS WITH MONTY GBLE. The most important finding is that Training Camp appeared to moderate the effect of prior knowledge on science outcomes, particularly for students with limited prior knowledge. This pattern across all outcome variables, suggests that strategy instruction may help offset challenges faced by students who lacked prior knowledge. Lacking automatic retrieval structures, students with lower prior knowledge often rely more on SRL strategies [44], and students appeared to use SRL strategies to monitor their understanding, overcome comprehension breakdowns, and build knowledge in real time. Because prior knowledge shapes both comprehension and retention [11] metacognitive strategies may have helped to focus attention and facilitate retrieval more effectively than passive studying [45]. These outcomes align with evidence that metacognitive accuracy training enhances learning, particularly reading comprehension [45] [46] and underscores its value in supporting learning in complex domains [48] [6].

Findings also underscore the broader potential of GBLEs to support reading comprehension and knowledge development. Although MISSIONS WITH MONTY was designed as an intervention, it offered students opportunities to practice metacognitive strategies and accuracy monitoring within an authentic problem-solving context. Integrated scaffolds highlight the potential to build domain knowledge by developing reading-specific SRL skills. Extending prior research linking integrated literacy instruction to comprehension gains via prior knowledge [21] [26] our findings suggest that students with low prior knowledge may struggle to engage with content-rich texts without effective strategies. Framing comprehension as “reading with a purpose” [49] reinforces the idea that reading is fundamentally a self-regulated learning process, anchored in student goals and driven by metacognition to bridge strategic reading and knowledge acquisition.

Findings of this study also shed new light on how to implement integrated, knowledge-building reading instruction in digital environments. Although current approaches to reading instruction emphasize integrated instruction designed to build knowledge [3] [19]; [26] our findings suggest that for students who lack such knowledge, metacognitive strategies combined with improved monitoring accuracy may function as a powerful bridge to deeper understanding. Our results advance both the Component Integration Framework of Reading (CIFR), which positions reading as both knowledge-based and knowledge-building [19], and the Active View of Reading (AVR) [19], which frames reading as a self-regulated process. Specifically, these results illustrate how the combination of metacognitive strategies and metacognitive monitoring accuracy training drive the acquisition of domain knowledge through reading comprehension. While the role of knowledge is clear, strategic reading that leads to knowledge acquisition is ultimately driven by students' ability to actively manage and regulate their own understanding of text.

This study is subject to several limitations. First, prior knowledge was assessed as a unidimensional construct, whereas contemporary research emphasizes its multidimensional nature, including structure, accuracy, and specificity, which may differentially influence comprehension and learning [11]. Future research should adopt more nuanced measures that capture the complexity of prior knowledge to better understand its role in learning. Also, the modest sample size constrains the generalizability of findings, and instructional fidelity, long-term retention, and transfer of strategy use to other contexts were not evaluated. Finally, individual differences such as motivation and language background were not accounted for, yet may play a critical role in shaping students' engagement with and benefit from GBLEs.

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