

Using digital prompts to support physics students' self-regulated learning

Louis Leblond^{1,*}, Ying Wang,² Jennelle L. Malcos,³ and Rayne A. Sperling^{4,†}

¹*Department of Physics, The Pennsylvania State University, University Park, Pennsylvania, USA*

²*U.S. Education, FHI 360, Durham, North Carolina, USA*

³*Department of Biology, The Pennsylvania State University, University Park, Pennsylvania, USA*

⁴*College of Education, The Pennsylvania State University, University Park, Pennsylvania, USA*



(Received 22 April 2025; accepted 14 January 2026; published 4 February 2026)

Research indicates that students learn effectively when they actively engage in planning, monitoring, and reflecting on their learning—a process known as self-regulated learning (SRL). This mixed-methods study examined the impact of a semester-long SRL intervention in an undergraduate physics course. In the first year, the instructor taught the course under standard conditions. The following year, after brief training sessions, the same instructor added digital prompts targeting various aspects of SRL to their course assignments. Results showed that students in this intervention group performed better on the final exam after controlling for preexisting self-efficacy, metacognitive awareness, and GPA. However, SRL outcomes did not increase in the intervention condition. Analysis of the prompts revealed that the instructor disproportionally focused on content- and management-related prompts and underutilized motivation, metacognition, and cognitive strategy prompts. Interview with the faculty indicated that the intervention was straightforward to implement, contributed to humanizing the course, and that additional training would have been desirable to help design prompts. Provided appropriate training and support structures are available, these findings show that integrating SRL strategies through digital prompts can be a practical and effective approach for supporting instructors in fostering students' SRL.

DOI: [10.1103/cfux-hfw5](https://doi.org/10.1103/cfux-hfw5)

I. INTRODUCTION

In physics education, we often encourage students to reflect on their learning by asking them to identify where they struggled, articulate what they found confusing, or evaluate their problem-solving approaches. These self-reflective activities are valuable, but they are not always enough. Reflection alone does not always lead to meaningful change; students may recognize their difficulties but remain uncertain about how to adjust their strategies, or they may lack the motivation to act on their insights. To be effective, self-reflection must be paired with actionable strategies and motivation that drive students to implement these strategies. In other words, students need structured support to not only recognize obstacles in their learning but also develop the skills and mindset necessary to address them.

Self-regulated learning (SRL) refers to students' ability to actively plan, monitor, and evaluate their learning processes and outcomes to achieve academic success [1–3]. Effective

SRL involves the coordination of cognition, metacognition, and motivation in response to academic tasks. For example, when completing a homework assignment, students must employ appropriate strategies (cognition), assess their understanding (metacognition), and sustain motivation to persist through challenges (motivation). Research suggests that structured instructional support can help students engage effectively in SRL and improve their learning outcomes [4–7]. In physics education research (PER), studies exploring holistic SRL approaches are scarce [8–11], and most research focuses on individual components of SRL.

For example, cognitive strategy use has been extensively studied in PER in the context of problem solving and conceptual learning. Studies on worked examples and scaffolding techniques indicate that guiding students through structured problem-solving processes has shown potential for improving transfer to novel problems [12,13]. Cognitive strategies also play a crucial role in many other aspects of coursework, both in- and out-of-class. In a recent study, Gjerde *et al.* [14] integrated three evidence-based cognitive strategies—elaborative encoding, retrieval practice, and self-explanation—into an introductory mechanics class. Students were given scaffolding tools (e.g., guiding questions and structured problem-solving formats) to support these strategies. Interviews revealed mixed uptake: retrieval practice (e.g., frequent quizzes or practice problems) was used extensively by students, whereas elaborative encoding and

*Contact author: lul29@psu.edu

†Contact author: rsd7@psu.edu

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

self-explanation were often partially implemented or completely ignored. This may suggest that students did not know how to use and coordinate multiple strategies and needed further support.

Metacognition, or the ability to monitor and regulate one's own learning, has also been widely studied in PER. Studies have demonstrated that metacognitive scaffolds, such as structured prompts encouraging students to reflect on their problem-solving approaches, can improve both conceptual understanding and performance in physics courses [15–18]. However, not all studies have shown positive effects. For example, Morphew [19] conducted an intervention focused on students' metacognition and reported that providing feedback was not effective for improving students' metacognitive monitoring accuracy. Other common examples of metacognitive exercises are exam preparation strategies such as structured practice exams and mock exams. These strategies can help students assess their readiness, but to maximize their impact, Zhang *et al.* [20] argue that such interventions should also incorporate other key aspects of self-regulated learning, such as motivation, cognitive strategies, and resource management.

Finally, motivation plays a central role in physics learning, influencing students' persistence, engagement, and performance. Several studies have examined self-efficacy, a key motivational construct that reflects students' confidence in their ability to succeed. Research indicates that students with higher physics self-efficacy are more likely to persist in physics courses and perform better on assessments [21–25]. In addition, research indicates that improving metacognition can also enhance self-efficacy, demonstrating the interconnected nature of SRL components [26].

While these single-SRL-component studies provide valuable insights and show some effectiveness in increasing students' learning outcomes, they lack a holistic, integrated approach that supports SRL development across multiple dimensions. One can think of this as “closing the loop.” We can encourage students to self-reflect on their problem-solving skills, but if we also increase their engagement or attend to their cognitive strategies use, meaningful progress is more likely. To maximize the benefits of SRL interventions, a holistic approach is needed—one that integrates cognitive strategies, metacognition, and motivation into a structured and supportive framework [27]. This approach is in alignment with the strong empirical and theoretical grounding that SRL components work in concert to improve learning and achievement [2,3].

Even with this evidence, however, implementing holistic SRL interventions can be challenging in practice. Many instructors perceive them as time-intensive or incompatible with the demands of teaching large, content-heavy physics courses [28,29]. In their systematic review of change strategies in undergraduate science, technology, engineering, and mathematics (STEM) education, Henderson *et al.*

[30] identify developing reflective teachers as one of four effective strategies. Successful change efforts in developing reflective teachers often provide instructors with individual or group consultation and feedback and create opportunities for instructors to reflect on their instructional practices and learn from their self-reflection.

In this study, we investigated the effectiveness of a digital prompt-based SRL intervention implemented in an undergraduate physics course. We used a mixed-method explanatory sequential design. In the quantitative phase, we analyzed the impact of the intervention on self-efficacy, metacognition, and academic performance. In the subsequent qualitative phase, we investigated how the intervention was perceived by the instructor in the study.

II. BACKGROUND AND RESEARCH QUESTIONS

Self-regulated learners actively plan, monitor, and evaluate their learning to improve their academic performance [1–3]. Unlike passive learning, where students rely solely on external instruction, SRL encourages learners to take an active role in managing their understanding, strategies, and motivation. Research has consistently shown that students who engage in SRL develop better problem-solving skills, higher persistence, and improved academic outcomes across disciplines, including STEM fields [6,7].

SRL is typically conceptualized as three interdependent components that work together to support student learning [31]:

1. **Cognition:** The selection and use of learning strategies, such as problem-solving approaches, elaboration, and distributed practice, to process information effectively.
2. **Metacognition:** The ability to monitor, regulate, and reflect on one's own thinking and learning progress. Students with strong metacognitive skills assess their understanding, adjust strategies when needed, and set learning goals.
3. **Motivation:** The willingness and effort to engage in learning. Motivational factors, such as self-efficacy, goal orientation, and interest in a subject, influence whether students persist in challenging academic tasks.

A. Empirical support for SRL interventions

Multiple meta-analyses and systematic reviews consistently indicate that SRL interventions, especially those that take a comprehensive approach, enhance college students' use of learning strategies and improve academic performance. For example, Jansen *et al.* [32] conducted a meta-analysis of 142 SRL intervention studies from 126 included articles in the higher education context. They reported that college students who received SRL interventions effectively improved their SRL activities as well as academic achievement. Furthermore, interventions that incorporated

both metacognitive and resource management strategies had a greater impact than those focusing on a single component, reinforcing the importance of multifaceted SRL intervention approaches.

Regarding SRL instruction methods, Jansen *et al.* [32] observed that the impact of direct SRL instruction on student achievement was smaller than previously reported by Dignath *et al.* [33] in primary school settings. They suggested that college students, who may already possess foundational learning strategies, benefit more from embedded SRL prompts and opportunities to apply SRL strategies in context rather than from explicit instruction alone. This finding underscores the potential of integrating SRL-supportive interventions within course activities to enhance students' engagement and academic success.

Similarly, Theobald's [34] meta-analysis of 49 studies found that SRL training effectively improved college students' academic performance, with metacognitive and resource management strategies being the most impactful. Additionally, SRL interventions have proven effective in online and hybrid learning environments, where self-directed learning is crucial for success. Broadbent and Poon's [6] systematic review of 12 studies lends further support and found that SRL strategies generally enhanced student learning. In particular, strategies such as time management, metacognition, effort regulation, and critical thinking were positively associated with improved academic outcomes in online settings.

Findings from these meta-analyses and systematic reviews highlight several key insights about SRL interventions in higher education. First, empirical research consistently demonstrates that SRL interventions enhance students' use of self-regulated learning strategies and improve academic performance. Second, student characteristics, such as age and prior experience with learning strategies, play a crucial role in intervention design. While some students may benefit from direct instruction on SRL strategies, college students—who often have prior exposure to various learning approaches—may respond more effectively to embedded SRL prompts and structured opportunities to apply these strategies in context. Third, SRL interventions yield larger benefits when they integrate multiple SRL components (e.g., metacognition, time management, and strategy use) rather than focusing on a single element, such as motivation alone.

Our intervention was built on these insights, ensuring an approach that aligns with evidence-based strategies for optimizing SRL development in higher education. We note that a holistic approach to SRL shares conceptual similarities with deliberate practice [35,36], which has been shown to enhance student outcomes in physics [37,38]. By incorporating structured, goal-directed activities with frequent feedback and reflection, deliberate practice aligns closely with the principles of self-regulated learning and offers promising avenues for further research.

B. The Success through Self-Regulated Learning framework

SRL interventions vary in structure. The present study was guided by the Success through Self-Regulated Learning (StSRL) framework, which was developed to support course instructors as they embed different SRL components into their regular teaching [39]. StSRL includes the three core components mentioned earlier—cognition, metacognition, and motivation—and adds to them content knowledge and management. Specifically, content focuses on maximizing learners' content learning, achievement, and transfer, such as making connections among multiple concepts. Management focuses on modeling and providing tools to support learners' time and resource management, such as directing students to resources. The StSRL framework suggests that these five components dynamically interact with one another to improve students' learning.

The intervention consisted of digital prompts embedded within the course content, targeting one or more components of the StSRL framework. The frequency and content of the prompts were determined by the instructor to align with students' needs at different points in the course. The prompts took different formats, from multiple-choice questions to short self-reflections. Here are two prompts that were given as examples to the instructor in this study:

- We are halfway through the semester. You can do it! Everyone can be successful in physics with the proper amount of dedicated time and with good learning strategies. Write inspiring advice for yourself or for a friend to help you or them finish the semester strong!
- What parts of the last two labs did you think were particularly helpful in your understanding?

The first example mostly targets motivation, management (what should you do), and cognitive strategies. The second prompt is more aligned with metacognition but also brings in content material. Previous research on StSRL has demonstrated positive increases in students' strategy use and learning outcomes [40,41].

Self-reflective exercises have been shown to yield positive outcomes in social-psychological utility-value interventions, often long after the course has ended [42]. Such interventions have also been effective in physics courses [43]. The intervention in our study differed from previous work in that, instead of one, often somewhat longer, self-reflective writing exercise, we asked students to respond to frequent small prompts. Additionally, the digital nature of the prompts allows for bidirectional discussions between the instructor and the students throughout the course, either individually or as a summary to the whole class.

For instructors who have been using this framework for many years, prompt design and implementation are a constant iterative process. In this study, we examined this intervention with a physics instructor new to the framework. The instructor was well-versed in active learning

pedagogy with a course design that already included learning strategies and activities that are known to support students' SRL, such as distributed practice [44] and peer learning.

C. Research questions

To evaluate the effectiveness of the prompts, this study compared a business-as-usual condition with an intervention condition, examining effects on students' self-efficacy, metacognitive awareness, and academic performance. We used the self-efficacy for strategic learning scale with two factors: higher- and lower-level strategic learning [45]. These factors are aligned with the revised Bloom taxonomy [46], with the lower-level aligned with *remember* and *understand*, while the higher level corresponds to *analyze* and *apply*. Additionally, we assessed the social validity of the intervention by conducting an interview with the course instructor. In this context, social validity refers to the acceptability or viability of an intervention [47]. In educational research, social validity is used to assess the extent to which an educational intervention is socially acceptable to student participants and other stakeholders, such as course instructors [48]. By integrating the quantitative and qualitative data strands, we aimed to further elaborate on the effectiveness of the intervention and to identify areas for improvement in future interventions. The research questions guiding our study are:

Research questions

1. Do students who received the SRL prompts have higher self-efficacy for higher- and lower-level strategic learning and metacognitive awareness than those who do not receive the prompts while controlling for GPA?
2. Do students in the intervention condition tend to perform better on the final exam than students in the business-as-usual condition while holding their self-efficacy for higher- and lower-level strategic learning, metacognitive awareness presurvey scores, and GPA constant?
3. What is the social validity of the intervention according to the instructor, and how does this relate to the quantitative findings?

III. METHODS

A. Research design

The study employed a mixed-method explanatory sequential design. We first conducted a quantitative intervention study to examine the effectiveness of the intervention, followed by a qualitative interview study to further explore the social validity of the intervention. In addition, we conducted a qualitative analysis of the instructor-created prompts to evaluate their alignment with the StSRL framework.

The research was carried out in the second course of the algebra-based introductory physics sequence at a large public university in the northeastern United States. This four-credit, large-enrollment course spans 15 weeks and covers selected topics in light, electricity, and magnetism. Data were collected across two semesters: Spring 2023 ($n = 494$), representing the business-as-usual condition, and Spring 2024 ($n = 458$), representing the intervention condition (total $n = 952$).

Both conditions followed the same three-part structure. First, students completed a presurvey. Second, students in the business-as-usual semester (Spring 2023) received regular instruction, while students in the intervention semester (Spring 2024) received prompts integrated into their postlecture quizzes. Prior to implementation, the instructor received training on designing and embedding prompts that align with the StSRL framework. Finally, students in both semesters completed the same postsurvey.

Survey completion rates were 78% (387/494) in the business-as-usual condition and 71% (324/458) in the intervention condition. For analysis, we only included students who completed both presurvey and postsurvey in either semester, yielding a matched sample of $n = 409$. Table I presents the demographic information for the matched dataset. Students received small extra credit incentives for completing both surveys.

TABLE I. Demographic information.

Business-as-usual—Spring 2023		
Ethnicity/race	Frequency	Percent (%)
Hispanic/Latino	8	3.4
White	153	64.8
Black/African American	10	4.2
Asian	17	7.2
Multiple	42	17.8
Other	6	2.6
Intervention—Spring 2024		
Ethnicity/race	Frequency	Percent (%)
Hispanic/Latino	8	3.6
White	126	57.8
Black/African American	7	3.2
Asian	27	12.4
Multiple	47	21.6
Other	3	1.4
Gender		
Male	44	22.7
Female	142	73.2
Other	8	4.1

Most students were enrolled in life science programs, such as biology and premedicine. Instruction included two weekly 50-min large lectures facilitated by undergraduate learning assistants [49] as well as weekly recitation and laboratory sections of ~30 students, each taught by graduate teaching assistants.

B. Implementation design and procedures

The same instructor taught both semesters, with lecture times and rooms nearly identical between conditions. The intervention began with preliminary discussions between the research team and the instructor to establish baseline course practices and introduce the StSRL framework. In total, approximately 2 h of meetings were held. The instructor was provided with sample prompts and models of implementation used by another physics instructor experienced with StSRL.

The instructor then independently designed the prompts, their mode of delivery, and the grading scheme. Prompts were embedded as the final question in short postlecture quizzes administered in the learning management system and given approximately twice per week. The postlecture quizzes were available immediately after the lecture and were due by the end of that day. In both conditions, quizzes were worth 2% of the course grade, with the lowest three scores dropped. Each quiz contained 4–5 physics questions (mostly multiple-choice). In the intervention semester, the instructor added prompts to 21 of 29 quizzes. Prompt formats included essay (6), multiple-answer (2), multiple-choice (10), matching (1), and numerical response (2).

Prompts were graded for correctness and counted equally with physics questions, making them worth ~15% of each quiz score (and ~0.3% of the overall course grade). The instructor graded the essay questions on a pass or fail basis on whether the students answered the question earnestly, with a fail for very brief answers, blanks, or text placeholders. In the Results section, we analyze the alignment of these prompts with the five components of the StSRL framework.

C. Measures

The presurvey and postsurvey instruments measured SRL constructs (self-efficacy and metacognition), as well as demographic variables, including self-reported GPA at the beginning of the semester. The main measures used in this study were:

1. *Self-efficacy for strategic learning in physics*: Self-efficacy is task and context dependent [50]. We administered the self-efficacy for strategic learning in physics scale, which was adapted from the same scale studied in the context of an undergraduate biology course [45]. The scale included 11 self-report items that examine students' higher- and lower-level

strategic learning. Students rated their perceived self-efficacy on a 100-point scale for each item, binned into ten-point intervals, and scored from 1 to 11. Cronbach's α was 0.84 for higher-level strategic learning and 0.93 for lower-level strategic learning for the presurvey and was 0.86 for higher-level strategic processing and 0.95 for lower-level strategic learning for the postsurvey.

2. *Metacognitive awareness*: We used the shortened Metacognitive Awareness Inventory (MAI) to measure students' metacognition [51,52]. The shortened version included 19 items describing knowledge of cognition and regulation of cognition. Students responded to the items on five-point Likert scales from 1 (Never) to 5 (Always). The overall Cronbach's α was 0.88 for the presurvey and was 0.91 for the postsurvey.
3. *Final exam scores*: Students took the same final exam in both study conditions. The exam was not returned to students at the end of the semester. The final exam consisted of 27 multiple-choice questions, each worth 1 point, and the final exam score was out of 25. The maximum score possible was 27/25 (or 108%).
4. *Postlecture quizzes with or without SRL prompt*: This is the average score for the post-lecture quizzes (worth 2% of the course grade in both conditions).

Table II reports descriptive statistics for the matched dataset. A total of 11 students were excluded from analyses because they were returning students who participated in both semesters. Students demonstrated high engagement with the postlecture quizzes, with median completion rates of 98% and 96% in the business-as-usual and intervention conditions, respectively.

All analyses were performed using R Statistical Software v4.4.1 [53] with the statistical packages LME4 [54], AFEX [55], and EMMEANS [56]. The analysis was also reproduced using SPSS v29.0 [57]. The data that support the findings of this article are openly available [58]. The full instruments are provided in the Appendix.

D. Qualitative phase

In the qualitative phase, we conducted a semistructured interview on Zoom with the instructor, facilitated by two interviewers. The transcript was analyzed using grounded theory [59,60] and independently coded by two of the authors using constant comparative methods followed by focused coding.

Coders then met to reconcile their codes and generate a summary. This phase occurred after quantitative analyses were completed, allowing us to integrate interview findings with survey results in line with our explanatory sequential design.

TABLE II. Descriptive statistics. *Note.* SD, standard deviation; LSL, lower-level strategic learning; HSL, higher-level strategic learning.

	Variable	Min	Max	Mean (SD)	Med
Spring 2023 Business-as-usual condition	Self-efficacy for LSL pre	8	66	44.9 (11.7)	47
	Self-efficacy for HSL pre	13	55	37.6 (9.0)	39
	Self-efficacy for LSL post	6	66	45.6 (12.0)	47
	Self-efficacy for HSL post	5	55	38.3 (9.8)	40
	Metacognitive awareness pre	37	94	70.5 (10)	71
	Metacognitive awareness post	22	95	70.2 (11.5)	70
	Postlecture quizzes	67	100	95.8 (6.0)	98
	GPA	2.1	3.99	3.57 (0.32)	3.6
	Final exam scores	28	108	70.1 (19.1)	72
Spring 2024 intervention condition	Self-efficacy for LSL pre	12	66	45.0 (11.1)	46
	Self-efficacy for HSL pre	10	55	37.9 (9.2)	39
	Self-efficacy for LSL post	6	66	46.1 (10.4)	48
	Self-efficacy for HSL post	5	55	39.5 (8.6)	41
	Metacognitive awareness pre	39	95	69.8 (10.1)	69
	Metacognitive awareness post	37	95	70.4 (10.5)	71
	Postlecture quizzes with SRL prompts	71	100	94.3 (6.6)	97
	GPA	2.1	3.99	3.59 (0.35)	3.7
	Final exam scores	20	104	75.1 (18.9)	80

IV. RESULTS

A. Intervention content analysis: Alignment of prompts with the StSRL framework

We remind the reader that the prompts were designed by the instructor following a brief training in the framework. To assess the quality and theoretical alignment of the intervention, we coded all 21 prompts according to the StSRL framework and rated their quality. Each prompt was assigned a primary StSRL category, and in some cases a secondary category, reflecting the strategy emphasized. Prompts were also rated on a three-tier scale of quality (low, medium, high).

The analysis showed that most prompts targeted content ($n = 9$) or management strategies ($n = 7$), with smaller numbers coded as metacognitive ($n = 4$) or motivational ($n = 1$), and none coded as cognitive learning strategy. In terms of quality, the majority of prompts were rated as medium quality ($n = 13$), while four prompts were rated as high quality and four prompts as low quality.

Table III presents four sample prompts to illustrate the range of formats and StSRL categories used in the intervention. A complete list of all 21 prompts, with coding and quality ratings, is provided in Supplemental Material [61].

These findings suggest that the intervention prompts could be mapped to the StSRL framework, but overall alignment was limited. The majority emphasized content and management strategies, with very few targeting meta-cognition or motivation, and none addressing cognitive learning strategies. In our team discussions, we agreed that while these prompts were generally aligned with the StSRL framework, many could have been refined with small

adjustments to more directly target self-regulated learning processes.

B. Research questions

Research question 1: Do students who received the SRL prompts have higher self-efficacy for higher- and lower-level strategic learning and metacognitive awareness than those who do not receive the prompts while controlling for GPA?

For research question 1, we were interested in examining the main and interaction effects of the SRL intervention and time on three outcome variables: students' self-efficacy for higher- and lower-level strategic learning and metacognitive awareness while controlling for GPA.

Repeated-measures analysis of covariance (ANCOVA) was conducted to examine the effect of condition (intervention vs business-as-usual) and time (pretest vs post-test) on the three SRL outcome variables, while controlling for GPA. The model included time as a within-subjects factor, condition as a between-subjects factor, and GPA as a covariate. Student ID was modeled as a random effect to account for repeated measures. To control for type I error across the three ANCOVAs, we applied a Bonferroni correction, yielding an adjusted significance threshold of $p < 0.017$.

Since our primary interest was in the impact of the intervention embedded in the postlecture quizzes, we excluded students with very low participation in these quizzes across both conditions. Specifically, we removed students whose overall postlecture quiz scores were more than three standard deviations below the mean (approximately 70% in both conditions). This procedure resulted

TABLE III. Example of prompts with type, primary/secondary matching StSRL categories and quality rating.

SRL prompt examples	Type	StSRL category primary and secondary	Quality and comments
1. What are your goals for this semester? Please list at least 3. (A grade can be one of them but think bigger and broader than just a grade.)	Essay	Motivation	High
2. How do you see this course fitting into your professional goals? (besides a program requirement, if it is one)			Good early prompt to target students' engagement
Health Promotion and Wellness offers a variety of programs for stress reduction and wellness. I encourage you to visit their site at XX. On Date XX their "Flourish Fair" described as "a fun, interactive opportunity for students to take a break and learn about mindfulness, stress management and sleep" will be held in:	Multiple-choice	Management	Med Remind students of resources for mental health. Would be enhanced by connecting more directly to the course itself
You are presented with a diagram showing lines circling around a point charge, and two points are marked. You are asked to determine the direction of the electric field at those two points and to compare the strength of the E field at those two points. What Unit 3 Objective does this problem best relate to? (Hint: go back to the Unit 3 page to review)	Numerical	Content, management	Med Good content and management question (find the objective). Would be enhanced with information on what to do next
What review resources are there for help preparing for MT2? (Select all that apply.)	Multiple select	Management	Low Management of finding resources. Would be enhanced with tips to students on how to use the resources.

in the exclusion of nine students. In addition, because GPA data were self-reported, some cases were missing; 60 students were excluded from analyses involving GPA for this reason, with roughly equal exclusion in both conditions. See Ref. [62] as support for the properties of students' self-reported GPA.

Results for self-efficacy for higher-level strategic learning indicated a significant main effect of GPA, $F(1, 337) = 25.01$, $p < 0.001$, such that students with higher GPA reported higher self-efficacy. No significant main effects were found for condition, $F(1, 337) = 0.43$, $p = 0.513$, or time, $F(1, 337) = 3.28$, $p = 0.071$. In addition, neither the condition $\times$ time interaction, $F(1, 337) = 1.06$, $p = 0.303$, nor the GPA $\times$ Time interaction, $F(1, 337) = 4.19$, $p = 0.041$, was significant under the Bonferroni-adjusted threshold of 0.017. Thus, higher-level self-efficacy appeared to be strongly associated with GPA but was not significantly influenced by the intervention or changes over time.

For self-efficacy for lower-level strategic learning, there was again a significant main effect of GPA, $F(1, 338) = 10.64$, $p = 0.001$. In addition, there was a significant main

effect of time, $F(1, 338) = 5.17$, $p = 0.024$, and a significant GPA $\times$ Time interaction, $F(1, 338) = 5.91$, $p = 0.016$. These findings suggest that students' lower-level strategic self-efficacy increased over time and that this change was moderated by GPA, with higher-GPA students showing greater gains.

For metacognitive awareness, only the main effect of GPA was significant, $F(1, 337) = 13.75$, $p < 0.001$. This indicates that students with higher GPAs also reported greater metacognitive awareness, but neither time nor the intervention condition had a significant effect.

Assumptions of ANCOVA were evaluated for all models. Visual inspection of Q-Q plots and histograms indicated that residuals were approximately normally distributed. Although Shapiro-Wilk tests were significant, this is not unexpected given the large sample size, and ANCOVA is robust to minor deviations from normality. Tests of homogeneity of variance (Levene's and Bartlett's) were nonsignificant across models, supporting the assumption of equal variances.

Research question 2: Do students in the intervention condition tend to perform better on the final exam than

TABLE IV. Hierarchical multiple linear regression with final exam as dependent variable. *Note.* $F(5, 333) = 45.09$, adjusted $R^2 = 0.395$, $p < 0.001$. B , β : Unstandardized, and standardized regression coefficients, SE : Standard error.

Step and predictor variable	B	$SE B$	β	p
Step 1:				
Self-efficacy for higher-level strategic learning presurvey	−0.066	0.159	−0.032	0.678
Self-efficacy for lower-level strategic learning presurvey	0.163	0.124	0.097	0.193
Metacognitive awareness presurvey	−0.153	0.089	−0.080	0.086
GPA	36.206	2.529	0.631	< 0.001
Step 2:				
Study condition	3.925	1.623	0.102	0.016

students in the business-as-usual condition while holding their self-efficacy for higher- and lower-level strategic learning, metacognitive awareness presurvey scores, and GPA constant?

Regarding the second research question, we examined whether students' final exam performance was predicted by the intervention condition while controlling for GPA and presurvey scores of self-efficacy for higher- and lower-level strategic learning and metacognitive awareness. These control variables were included to account for individual differences that might influence how students responded to the intervention [63]. By holding these factors constant, we were able to better isolate the unique effect of the intervention on final exam performance.

A hierarchical multiple regression model including GPA, self-efficacy for strategic learning (higher- and lower-level), metacognitive awareness, and study condition was statistically significant, $F(5, 333) = 45.09$, $p < 0.001$, adjusted $R^2 = 0.40$. Among the predictors, GPA was the strongest positive predictor of final exam performance ($p < 0.001$). Importantly, study condition also emerged as a significant predictor ($B = 3.93$, $SE = 1.62$, $\beta = 0.10$, $p = 0.016$), such that students who received the SRL prompts scored approximately 4% higher on the final exam compared to students in the business-as-usual condition. This represents a small effect size (Cohen's $d \approx 0.27$).

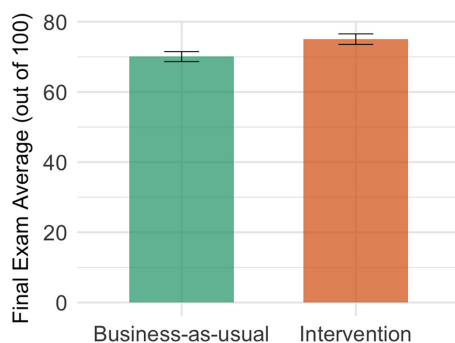


FIG. 1. Mean final exam score between the business-as-usual condition and intervention condition.

See Table IV for the regression model summary and Fig. 1 for a visualization of exam performance across conditions.

Research question 3: What is the social validity of the intervention according to the instructor, and how does it relate to the quantitative findings?

To assess the social validity of the intervention, we conducted a semistructured interview with the course instructor to understand their experience implementing the SRL prompts, their perceptions of prompt effectiveness, and the feasibility of sustaining such interventions in future courses. We identified five themes in our analysis: implementation, prompt design, knowledge of SRL, instructor perceived impact, and instructor training. Figure 2 includes sample quotes.

Implementation: The instructor reported a few technical challenges in implementing the SRL intervention. Initially, they provided individualized feedback on students' open-ended responses, but soon realized that students rarely viewed these comments. Additionally, responding individually became too time consuming. As a result, they transitioned to using multiple-choice, numerical, or multiple-select questions to streamline the grading of the prompts; see Fig. 2(a). We also note that this is where they transitioned to prompts that were more content and management oriented (see, for example, prompts 5–10 in Supplemental Material [61]).

Prompts design: Regarding the intended purpose of the prompts, the instructor saw them as serving multiple functions: activating prior knowledge, providing motivation, and reminding students about available resources. Perhaps most notably, they felt that the intervention helped to humanize the course, fostering a sense of connection between the instructor and students despite the large class size.

Knowledge of SRL: The instructor had a good understanding of self-regulated learning (SRL) and already structured the course around principles of distributed practice [see Fig. 2(c)]. As part of the interview, we presented the instructor with a list of learning strategies. They noted that organizational strategies seemed less useful for their students, whereas rehearsal-based strategies, peer learning, and elaboration aligned better with their instructional approach.

- (a) *"If I asked anything open-ended to grade. It meant I'm giving up a full workday to grade all those. After doing that a few times, I'm like, alright, I gotta do some of these that are multiple choice that are still nudging them towards a resource or something."*
- (b) *"And the 1st one [prompt] I really liked a lot, because I simply asked them goals for the course or concerns they have, and some people had some really good ones. I ended up writing a lot of responses"*
- (c) *"The course is 6 units, and for each 2 units. There's an exam [...] and so before each exam, there are 2 quizzes at the testing center. [...] it is essentially a way of having them take a proctored exam before the exam. To give them a real sense of how prepared they are".*
- (d) *"did I think anything radically change or significantly change over the course of the semester? I don't think I would really be able to tell. I guess I was sort of hoping that maybe exam scores would go up or something like that. I'm not sure that they did, but that may not be the best measure."*
- (e) *"I'd be happy to get feedback on the questions I use, or see more examples of other people using, because, I don't claim there's anything particularly great about the questions that I did. [...] the problem is that you had [provided] some good [example prompts] questions, but they just sort of didn't work for my class for various reasons. Just because they're different audiences, but it would be, interesting to see what other people have done and just get ideas."*

FIG. 2. Sample quotes.

Instructor perceived impact: In terms of perceived impact, the instructor was uncertain whether the prompts had any measurable effect on student performance. They initially hoped to see improvements on exams but did not observe clear evidence of such gains. When asked whether reminders about office hours led to increased attendance, they responded that they did not notice any difference. While they were unsure about the overall effectiveness of the intervention, they emphasized that the most meaningful impact was in creating a sense of instructor-student interaction, reinforcing their perception that humanization was the intervention's greatest strength. The instructor particularly liked the first prompt, which asked students about their academic goals, but expressed less enthusiasm for others, such as the prompt asking students to predict their grades on a midterm exam. They indicated a preference for open-ended responses but acknowledged that grading and responding to such answers at scale would require improved technological support [see Figs. 2(b) and 2(d)].

Instructor training: Finally, the instructor received only minimal training on the intervention and largely relied on their own intuition when creating the prompts. While they initially downplayed the need for additional training, they later acknowledged that having a structured framework or comparisons of effective prompt-design strategies might have been beneficial. They expressed openness to refining the approach in the future, particularly if improvements in technology could better support student-instructor interactions [see Fig. 2(e)].

V. DISCUSSION AND LIMITATIONS

By comparing a business-as-usual condition with an intervention condition, this study examined whether embedding prompts aligned with an empirically driven

StSRL framework influenced students' self-regulated learning constructs and learning outcomes. Overall, the intervention did not significantly impact students' self-efficacy for strategic learning (higher- or lower-level) or their metacognitive awareness. The only significant quantitative effect was an increase in the final exam for the students in the intervention condition. We remind the reader that the final exam was exactly the same in both study conditions. However, this finding should be interpreted cautiously given the presence of potential confounding factors and the small effect size.

A. Integration of quantitative and qualitative findings

The integration of our quantitative and qualitative findings provides a more nuanced understanding of the impact of the intervention. The quantitative analysis showed no measurable impact of the intervention on SRL constructs. A key insight from the qualitative findings is that the intervention was constrained by limited instructor training and implementation hurdles. Due to the large size of the class and the technological limits of the learning management system, the instructor shifted away from open-ended responses to multiple-choice and numerical formats. Additionally, the instructor reported that more training and examples could have been useful, as they mostly relied on their own intuition when creating the prompts. Our coding analysis confirmed that the prompts were disproportionately focused on content and management strategies, with fewer targeting metacognition, motivation, and cognitive learning strategy. While these prompt types were broadly aligned with the StSRL framework, many could have been improved with small adjustments to more directly support planning, monitoring, and reflection—core processes of self-regulated learning. This helps explain why we observed limited effects on SRL measures: the

intervention may not have consistently targeted the constructs it was designed to enhance.

Another important factor in interpreting the results is the preexisting instructional design of the course. The course was designed around principles of distributed practice and peer learning, which are known to promote SRL. Given this, our intervention functioned more as a small perturbation within an already well-structured learning environment rather than a major instructional shift. Yet, despite this, the intervention still had a measurable impact on the final exam and on the instructor's perceptions.

B. Limitations

Several limitations should be considered when interpreting these findings. First, although the course structure remained largely consistent across semesters, the instructor also introduced a lecture participation grade in the intervention semester. While this grade was not directly tied to exam outcomes, it may have influenced student engagement and therefore contributed indirectly to performance differences between conditions. We treat this as a confounding factor that limits the strength of causal claims about the effect of the prompts on final exam performance. However, it is important to note that the study sample consisted of students who already demonstrated very high participation rates in the course overall, as seen in the postlecture quiz scores. For this highly engaged subset of students, the added lecture participation grade likely had less impact, reducing the concern that it drove the observed differences.

Second, although the same instructor taught both semesters, differences in teaching assistants or in instructor engagement between semesters could have influenced student outcomes.

Third, our analysis included students who completed both the presurvey and postsurvey, likely capturing the most motivated students who consistently engaged with the course in both conditions. While this approach strengthens the internal validity of our study, it introduces another limitation: our findings do not generalize to all enrolled students. However, we argue that this selection criterion is necessary for the analysis to be meaningful. It also helps mitigate the impact of grading lecture participation, as these students were more likely to attend lectures in both conditions.

Finally, while we did not directly control for students' prior physics knowledge, we did include self-reported GPA as a covariate, which likely captured a substantial portion of the variance associated with prior academic preparation. Given the stability of the student population across semesters in this course, differences in prior physics knowledge are therefore unlikely to account for the observed effects.

C. Final thoughts

While possible confounding factors and the lack of significant improvement in students' self-regulated learning outcomes limit the strength of the findings, the study

remains informative. Although the instructor implemented the intervention with limited training and some misalignment between the prompts and the intended SRL constructs, the approach was still feasible to deploy in a large-enrollment course. The instructor ultimately developed 21 prompts, of which 4 were rated as high-quality and well aligned with the StSRL framework, while others demonstrated partial or moderate alignment. Even with this uneven quality, the intervention produced a modest but statistically significant gain in final exam performance and was perceived by the instructor as humanizing the course.

Importantly, in follow-up discussions, we learned that the instructor has continued to use and refine these prompts in subsequent semesters. They reported having resolved some initial implementation challenges, such as the grading of open-ended responses. This continued use highlights the intervention's practicality and durability over time.

Future implementations should focus on helping instructors design prompts that move beyond content reinforcement and logistical reminders toward fostering planning, monitoring, and reflection. Even small adjustments in wording—for example, asking students how they will approach learning a concept rather than what the concept is—could strengthen alignment with the StSRL framework. Additional training, technological support, and examples of high-quality prompts may be necessary to achieve larger and more consistent effects on students' self-regulated learning.

Future research could explore how prompts like the ones used in this study might be paired with more targeted interventions focused on specific components of self-regulated learning. For example, Gjerde and collaborators have conducted extensive work on supporting students in using various learning strategies such as retrieval practice [64–66]. It is possible that the effectiveness and perceived value of these strategies could be enhanced when combined with prompts that explicitly support those strategies and other phases of the SRL cycle. Future research may also target students' perceptions and value of the prompts as tools for their academic success. In related research with biology students, two thirds of students using the intervention reported that it was helpful to their success in the course [67]. Further, students in previous sections of physics have noted the value of the prompts when completing their course evaluations. Students' feedback would also benefit instructor training and implementation.

VI. CONCLUSIONS

A substantial body of research demonstrates the importance of supporting students' self-regulated learning (SRL). The central challenge is not whether SRL support is beneficial, but how instructors can feasibly embed such support within authentic instructional settings, especially in large-enrollment courses.

This study contributes to the field by examining a deliberately lightweight SRL intervention grounded in the Success through Self-Regulated Learning (StSRL) framework. The intervention was designed to be conceptually accessible to instructors, require minimal training, and integrate into existing course structures. Although no statistically significant changes were observed in students' self-efficacy or metacognitive awareness, the intervention was associated with a statistically significant improvement in final exam performance. Given the small effect size and the presence of potential confounding variables, these findings should be interpreted cautiously. Nonetheless, they suggest that even minimal, embedded SRL supports may have measurable effects on learning outcomes.

The results also highlight important implementation considerations. Partial misalignment between the prompts and the StSRL framework points to the potential value of increased instructor training and reduced technological constraints. More broadly, supporting SRL extends beyond any single course: helping students develop self-regulatory skills can contribute to transferable learning practices that benefit them across subsequent science courses and beyond their university studies.

ACKNOWLEDGMENTS

This work was supported by an NSF IUSE No. DUE2337176. The study was approved by the Institutional Review Board. All human subjects consented to their participation in the study. As recommended by Ref. [68], we acknowledge the use of ChatGPT-4o during the writing process of this manuscript between October 2024 and April 2025. The tool was used to enhance language clarity and correct grammatical errors only (e.g., ChatGPT prompt: rewrite [sentence] or summarize [sentence]). We (as authors) have reviewed and edited the text, and thus take full responsibility for the manuscript, regardless of how ChatGPT-4o influenced its creation. L. L. wants to thank Jes Matsick and Neil Hatfield, who— together with coauthor R. S. serve as mentors under NSF BCSE No. 2422432. We would like to thank Charles Henderson and Stephen Van Hook for their feedback on the manuscript.

DATA AVAILABILITY

The data that support the findings of this article are openly available [58].

APPENDIX: INSTRUMENTS

Physics self-efficacy inventory

This scale was adapted from the Self-Efficacy for Strategic Learning in Biology Scales (SESLBS) [45].

Items 1 and 2 are *outcome expectancies* for the class.

Items 3–7 were identified in [45] to be in the *Higher-level Strategic Learning* category, while items 8–13 are in the *Lower-level Strategic Learning* category.

Item instructions: Please rate your confidence for the following questions from 0% confident to 100% confident.

How confident are you that, right now, you ...

Anchors: 0% Cannot do at all to 100% Highly certain can do.

Items:

1. ... will be successful in your current physics course?
2. ... will be successful in an advanced physics course?
3. ... could analyze a set of data (i.e., look at the relationships between variables)?
4. ... could tutor another student for your current general physics course?
5. ... could ask a meaningful question that could be answered experimentally?
6. ... could explain something that you learned in your current physics course to a non-science person?
7. ... you could use a scientific approach to solve a problem at home?
8. ... after reading an article about a physics experiment, you could write a summary of its main points?
9. ... after reading an article about a physics experiment, you could explain its main ideas to another person?
10. ... after watching a television documentary dealing with some aspect of physics you could write a summary of its main points?
11. ... after watching a television documentary dealing with some aspect of physics, you could explain its main ideas to another person?
12. ... after listening to a public lecture regarding some physics topic, you could write a summary of its main points?
13. ... after listening to a public lecture regarding some physics topic, you could explain its main ideas to another person?

Metacognitive awareness inventory

We use a shortened version of the Metacognitive Awareness Inventory (MAI) [51,52]. Item 1–8 fall into the knowledge of cognition category, while items 9–19 measure regulation of cognition.

Item instructions: Think about the current course in which you are enrolled that invited you to take this survey, or related courses you have taken in the past, as you rate these items.

Please indicate how typical of you each item is.

Anchors: 1 = Not at all typical of me to 5 = Very typical of me.

Items:

1. I know what kind of information is most important to learn.

2. I know what the teacher expects me to learn.
3. I have control over how well I learn.
4. I can motivate myself to learn when I need to.
5. I am aware of what strategies I use when I study.
6. I am a good judge of how well I understand something.
7. I find myself using helpful learning strategies automatically.
8. I know when each strategy I use will be most effective.
9. I think about what I really need to learn before I begin a task.
10. I set specific goals before I begin a task.
11. I try to translate new information into my own words.
12. I use the organizational structure of the text to help me learn.
13. I ask myself if what I'm reading is related to what I already know.
14. I periodically review to help me understand important relationships.
15. I summarize what I've learned after I finish.
16. I ask myself if I learned as much as I could have once I finish a task.
17. I change strategies when I fail to understand.
18. I reevaluate my assumptions when I get confused.
19. I stop and go back over the new information that is not clear.

-
- [1] B. J. Zimmerman, Attaining self-regulation: A social cognitive perspective, in *Handbook of Self-Regulation* (Elsevier, New York, 2000), pp. 13–39.
 - [2] P. H. Winne and A. F. Hadwin, Studying as self-regulated learning, in *Metacognition in Educational Theory and Practice* (Lawrence Erlbaum Associates, Mahwah, NJ, 1998), pp. 277–304.
 - [3] B. J. Zimmerman and A. R. Moylan, Self-regulation: Where metacognition and motivation intersect, in *Handbook of Metacognition in Education* (Routledge, New York, 2009), pp. 299–315.
 - [4] A. S. Donker, H. De Boer, D. Kostons, C. D. Van Ewijk, and M. P. van der Werf, Effectiveness of learning strategy instruction on academic performance: A meta-analysis, *Educ. Res. Rev.* **11**, 1 (2014).
 - [5] C. A. Wolters and L. D. Hoops, Self-regulated learning interventions for motivationally disengaged college students, in *Self-Regulated Learning Interventions with At-Risk Youth: Enhancing Adaptability, Performance, and Well-Being*, edited by T. J. Cleary (American Psychological Association, Washington, DC, 2015), pp. 67–88.
 - [6] J. Broadbent and W. L. Poon, Self-regulated learning strategies & academic achievement in online higher education learning environments: A systematic review, *Internet Higher Educ.* **27**, 1 (2015).
 - [7] B. J. Zimmerman and D. H. Schunk, Self-regulated learning and performance: An introduction and an overview, in *Handbook of Self-Regulation of Learning and Performance* (Routledge, New York, 2011), pp. 1–12.
 - [8] N. Achufusi-Aka and F. Offiah, The effect of self-regulated learning on academic achievement of secondary school physics students, *Afr. J. Educ. Stud. Math. Sci.* **8**, 29 (2010).
 - [9] O. V. Anayo, The relationship between self-regulated learning and students' learning outcomes in physics, *Sapientia Found. J. Educ. Sci. Gender Stud.* **5** (2023), <https://sfjesgs.com/index.php/SFJESGS/article/view/397>.
 - [10] D. Maldonado and J. Stewart, Adding self-regulated learning instruction to an introductory physics class, *presented at PER Conf. 2023*, [10.1119/perc.2023.pr.Maldonado](https://doi.org/10.1119/perc.2023.pr.Maldonado).
 - [11] G. W. Rieger, J. McIver, S. Mazabel, and E. W. Burkholder, Supporting students' self-regulated learning in an introductory physics course, *Phys. Teach.* **61**, 18 (2023).
 - [12] T. J. Nokes-Malach, K. VanLehn, D. M. Belenky, M. Lichtenstein, and G. Cox, Coordinating principles and examples through analogy and self-explanation, *Eur. J. Psychol. Educ.* **28**, 1237 (2013).
 - [13] T. Van Gog and N. Rummel, Example-based learning: Integrating cognitive and social-cognitive research perspectives, *Educ. Psychol. Rev.* **22**, 155 (2010).
 - [14] V. Gjerde, B. Holst, and S. D. Kolstø, Integrating effective learning strategies in basic physics lectures: A thematic analysis, *Phys. Rev. Phys. Educ. Res.* **17**, 010124 (2021).
 - [15] A. Mason and C. Singh, Do advanced physics students learn from their mistakes without explicit intervention?, *Am. J. Phys.* **78**, 760 (2010).
 - [16] A. R. Mota, N. Didiş Körhasan, K. Miller, and E. Mazur, Homework as a metacognitive tool in an undergraduate physics course, *Phys. Rev. Phys. Educ. Res.* **15**, 010136 (2019).
 - [17] E. Sijmkens, M. De Cock, and T. De Laet, Scaffolding students' use of metacognitive activities using discipline- and topic-specific reflective prompts, *Metacognit. Learn.* **18**, 811 (2023).
 - [18] G. Taasooobshirazi and J. Farley, Construct validation of the physics metacognition inventory, *Int. J. Sci. Educ.* **35**, 447 (2013).
 - [19] J. W. Morphew, Changes in metacognitive monitoring accuracy in an introductory physics course, *Metacognit. Learn.* **16**, 89 (2021).
 - [20] M. Zhang, J. Morphew, and T. Stelzer, Impact of more realistic and earlier practice exams on student metacognition, study behaviors, and exam performance, *Phys. Rev. Phys. Educ. Res.* **19**, 010130 (2023).

- [21] Y. Li and C. Singh, Effect of gender, self-efficacy, and interest on perception of the learning environment and outcomes in calculus-based introductory physics courses, *Phys. Rev. Phys. Educ. Res.* **17**, 010143 (2021).
- [22] A. Madsen, S. B. McKagan, and E. C. Sayre, How physics instruction impacts students' beliefs about learning physics: A meta-analysis of 24 studies, *Phys. Rev. ST Phys. Educ. Res.* **11**, 010115 (2015).
- [23] J. M. Nissen and J. T. Shemwell, Gender, experience, and self-efficacy in introductory physics, *Phys. Rev. Phys. Educ. Res.* **12**, 020105 (2016).
- [24] V. Sawtelle, E. Brewe, and L. H. Kramer, Exploring the relationship between self-efficacy and retention in introductory physics, *J. Res. Sci. Teach.* **49**, 1096 (2012).
- [25] G. Taasobshirazi and M. Carr, A structural equation model of expertise in college physics, *J. Educ. Psychol.* **101**, 630 (2009).
- [26] J. L. Nietfeld, L. Cao, and J. W. Osborne, The effect of distributed monitoring exercises and feedback on performance, monitoring accuracy, and self-efficacy, *Metacognit. Learn.* **1**, 159 (2006).
- [27] Y. Wang and R. A. Sperling, Characteristics of effective self-regulated learning interventions in mathematics classrooms: A systematic review, *Front. Educ.* **5**, 58 (2020).
- [28] E. Yerushalmi, C. Henderson, K. Heller, P. Heller, and V. Kuo, Physics faculty beliefs and values about the teaching and learning of problem solving. I. Mapping the common core, *Phys. Rev. ST Phys. Educ. Res.* **3**, 020109 (2007).
- [29] M. Dancy and C. Henderson, Framework for articulating instructional practices and conceptions, *Phys. Rev. ST Phys. Educ. Res.* **3**, 010103 (2007).
- [30] C. Henderson, A. Beach, and N. Finkelstein, Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature, *J. Res. Sci. Teach.* **48**, 952 (2011).
- [31] B. J. Zimmerman, Becoming a self-regulated learner: An overview, *Theory Pract.* **41**, 64 (2002).
- [32] R. S. Jansen, A. Van Leeuwen, J. Janssen, S. Jak, and L. Kester, Self-regulated learning partially mediates the effect of self-regulated learning interventions on achievement in higher education: A meta-analysis, *Educ. Res. Rev.* **28**, 100292 (2019).
- [33] C. Dignath, G. Buettner, and H.-P. Langfeldt, How can primary school students learn self-regulated learning strategies most effectively?: A meta-analysis on self-regulation training programmes, *Educ. Res. Rev.* **3**, 101 (2008).
- [34] M. Theobald, Self-regulated learning training programs enhance university students' academic performance, self-regulated learning strategies, and motivation: A meta-analysis, *Contemp. Educ. Psychol.* **66**, 101976 (2021).
- [35] K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer, The role of deliberate practice in the acquisition of expert performance, *Psychol. Rev.* **100**, 363 (1993).
- [36] E. T. Torigoe, Emphasizing expert practice with spaced recall, *arXiv:1508.00470*.
- [37] D. J. Jones, K. W. Madison, and C. E. Wieman, Transforming a fourth year modern optics course using a deliberate practice framework, *Phys. Rev. ST Phys. Educ. Res.* **11**, 020108 (2015).
- [38] A. Price and C. Wieman, Improved teaching of science and engineering using deliberate practice of problem-solving decisions, *Innovative Teach. Learn.* **5**, 1 (2023).
- [39] R. Sperling, Supporting success through educational technology innovations: Prompting students' self-regulated learning, The Center for Innovation in Online Learning (COIL) and Collaborative Match, The Pennsylvania State University, University Park, PA (2017).
- [40] J. C. Tise, R. A. Sperling, J. L. Malcos, and P. Buchanan, Use of a technology-based SRL tool predicts course performance—but response latency moderates the effect, in *Proceedings of the American Educational Research Association Annual Meeting, Chicago, IL* (2023).
- [41] J. L. Malcos, Y. Wang, and R. A. Sperling, The role of student responses to instructor-generated SRL (self-regulated learning) prompts on student performance and self-efficacy, in *Proceedings of the American Educational Research Association Annual Meeting, Philadelphia, PA* (2024).
- [42] D. S. Yeager and G. M. Walton, Social-psychological interventions in education: They're not magic, *Rev. Educ. Res.* **81**, 267 (2011).
- [43] K. R. Binning, N. Kaufmann, E. M. McGreevy, O. Fotuhi, S. Chen, E. Marshman, Z. Y. Kalender, L. Limeri, L. Betancur, and C. Singh, Changing social contexts to foster equity in college science courses: An ecological-belonging intervention, *Psychol. Sci.* **31**, 1059 (2020).
- [44] N. J. Cepeda, H. Pashler, E. Vul, J. T. Wixted, and D. Rohrer, Distributed practice in verbal recall tasks: A review and quantitative synthesis, *Psychol. Bull.* **132**, 354 (2006).
- [45] Y. Wang, R. A. Sperling, and P. M. Reeves, A validation study of the Self-Efficacy for Strategic Learning in Biology Scales (SESLS), *Int. J. Educ. Res. Open* **5**, 100302 (2023).
- [46] L. W. Anderson, D. R. Krathwohl, P. W. Airasian, K. A. Cruikshank, R. E. Mayer, P. R. Pintrich, J. Rath, and M. C. Wittrock, *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, Complete Edition (Longman, New York, 2001).
- [47] I. S. Schwartz and D. M. Baer, Social validity assessments: Is current practice state of the art?, *J. Appl. Behav. Anal.* **24**, 189 (1991).
- [48] E. Ogilvie and M. T. McCrudden, Evaluating the social validity of the early start Denver model: A convergent mixed methods study, *J. Autism Dev. Disord.* **47**, 2899 (2017).
- [49] V. Otero, S. Pollock, and N. Finkelstein, A physics department's role in preparing physics teachers: The Colorado learning assistant model, *Am. J. Phys.* **78**, 1218 (2010).
- [50] A. Bandura, Self-efficacy: Toward a unifying theory of behavioral change, *Psychol. Rev.* **84**, 191 (1977).
- [51] G. M. Harrison and L. M. Vallin, Evaluating the metacognitive awareness inventory using empirical factor-structure evidence, *Metacognit. Learn.* **13**, 15 (2018).
- [52] G. Schraw and R. S. Dennison, Assessing metacognitive awareness, *Contemp. Educ. Psychol.* **19**, 460 (1994).
- [53] R Core Team, *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, Vienna, Austria, 2021).

- [54] D. Bates, M. Mächler, B. Bolker, and S. Walker, Fitting linear mixed-effects models using LME4, *J. Stat. Softw.* **67**, 1 (2015).
- [55] H. Singmann, B. Bolker, J. Westfall, F. Aust, and M. S. Ben-Shachar, afex: Analysis of Factorial Experiments, R package version 1.4-1 (2024), <https://CRAN.R-project.org/package=afex>.
- [56] R. V. Lenth, emmeans: Estimated Marginal Means, aka Least-Squares Means, R package (2024), <https://CRAN.R-project.org/package=emmeans>.
- [57] I. B. M. Corp, *IBM SPSS Statistics for Windows, Version 29.0* (IBM Corp., Armonk, NY, 2023).
- [58] L. Leblond, Y. Wang, J. Malcos, and R. Sperling, Using digital prompts to support physics students self-regulated learning, [10.5281/zenodo.15263400](https://doi.org/10.5281/zenodo.15263400).
- [59] K. Charmaz, *Constructing Grounded Theory*, 2nd ed. (Sage, Los Angeles, CA, 2014).
- [60] A. Strauss, J. Corbin *et al.*, *Basics of Qualitative Research* (Sage, Newbury Park, CA, 1990), Vol. 15.
- [61] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/cftx-hfw5> for a list of digital SRL prompts used in the study with their types, StSRL categories, and quality ratings.
- [62] J. A. Rosen, S. R. Porter, and J. Rogers, Understanding student self-reports of academic performance and course-taking behavior, *AERA Open* **3** (2017).
- [63] R. Theobald and S. Freeman, Is it the intervention or the students? Using linear regression to control for student characteristics in undergraduate STEM education research, *CBE Life Sci. Educ.* **13**, 41 (2014).
- [64] V. Gjerde, V. Havre Paulsen, B. Holst, and S. D. Kolstø, Problem solving in basic physics: Effective self-explanations based on four elements with support from retrieval practice, *Phys. Rev. Phys. Educ. Res.* **18**, 010136 (2022).
- [65] V. Gjerde, M. Marisaldi, K. Oksavik, K. Olafsson, H. Spångberg, and B. Holst, Mandatory retrieval test to incentivize retrieval practice of physics principles, *Phys. Rev. Phys. Educ. Res.* **21**, 010119 (2025).
- [66] V. Gjerde, B. Holst, and S. D. Kolstø, Retrieval practice of a hierarchical principle structure in university introductory physics: Making stronger students, *Phys. Rev. Phys. Educ. Res.* **16**, 013103 (2020).
- [67] J. L. Malcos, J. C. Tise, and R. A. Sperling, Resource use in a large introductory physiology course, in *Proceeding of the Human Anatomy and Physiology Society (HAPS) Annual Conference, Portland, OR* (2019).
- [68] K.-S. Tang, G. Cooper, and W. Nielsen, Philosophical, legal, ethical, and practical considerations in the emerging use of generative AI in academic journals: Guidelines for research in science education (RISE), *Res. Sci. Educ.* **54**, 797 (2024).