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NEURO ADAPTIVE METACOGNITIVE PROMPTING STRATEGIES FOR IMPROVING SELF REGULATED LEARNING AND CRITICAL THINKING IN PSYCHOLOGICAL SCIENCE EDUCATION

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SUMMARY

The growing recognition of Psychological Science education as a domain that demands higher-level thinking has revealed that students still exhibit chronic shortcomings in self-regulated learning (SRL) and critical thinking. Reports indicate that about 42% of undergraduate psychology students have low metacognitive monitoring accuracy, and more than 38% do not transfer conceptual knowledge to practice. This study assesses the use of Neuro Adaptive Metacognition Prompting Strategies (NAMPS) to develop SRL and critical thinking in undergraduate psychology courses. A quasi-experimental design with N = 184 (control n = 92, intervention n = 92) across two academic semesters was used. Cognitive load and neurocognitive feedback served as the guiding principles for the integrated metacognitive prompts in the intervention. Intervention tests were administered before and after the intervention with the Metacognitive Awareness Inventory (MAI) and the Critical Thinking Assessment (CTA). A repeated-measures ANOVA and a hierarchical regression model were executed to assess the outcomes. Findings showed statistically significant changes in the intervention group compared with controls. The scores of SRL were raised by 27.4% ($p < .001$, $\eta2 = .31$). The performance on critical thinking was enhanced by 22.8% ($p < .001$, $\eta2 = .28$). The results of the regression analysis showed that the metacognitive monitoring accuracy explained 34% of the variance in the post-test critical thinking scores ($R2 = .34$, $p < .001$). The effect sizes were moderate and large (Cohen's $d = 0.62$-0.81). The results indicate that Neuro Adaptive Metacognitive Prompting Strategies are highly effective in improving students' regulatory skills and analytical thinking in the study of psychological sciences. The research justifies the application of adaptive metacognitive scaffolds in curriculum development to promote lasting cognitive growth and academic success.

Key words: *neuro-adaptive prompting, metacognitive strategies, self-regulated learning (SRL), critical thinking, psychological science education, metacognitive monitoring accuracy, adaptive instructional design.*

INTRODUCTION

Neuro-adaptive metacognitive prompting is an instructional model that combines concepts from educational neuroscience with dynamic metacognitive scaffolding to enhance learners' regulatory control over cognition. It involves real-time or performance-contingent stimuli with an understanding of the neural processes that govern executive functioning, working memory, and cognitive monitoring. Metacognition encompasses cognition, knowledge, and cognitive regulation, which are planning, monitoring, and cognitive evaluation [1]. In this regard, neuroadaptive prompting provides a feedback -based error-monitoring system and metacognitive judgment, involving prefrontal cortical activation and the adjustment of prompts based on learners' cognitive load and metacognitive accuracy [3]. The rationale for such adaptive mechanisms is that failures in strategy use and understanding enhance metacognitive skills in learners when learners have access to systematic means to reflect on (Stanton et al., 2021). Moreover, neuroscience-based teacher preparation emphasises the need to incorporate brain-based concepts into pedagogical interventions [6]. Therefore, neuroadaptive metacognitive prompting builds upon traditional scaffolding by integrating neurocognitive sensitivity into the instructional design.

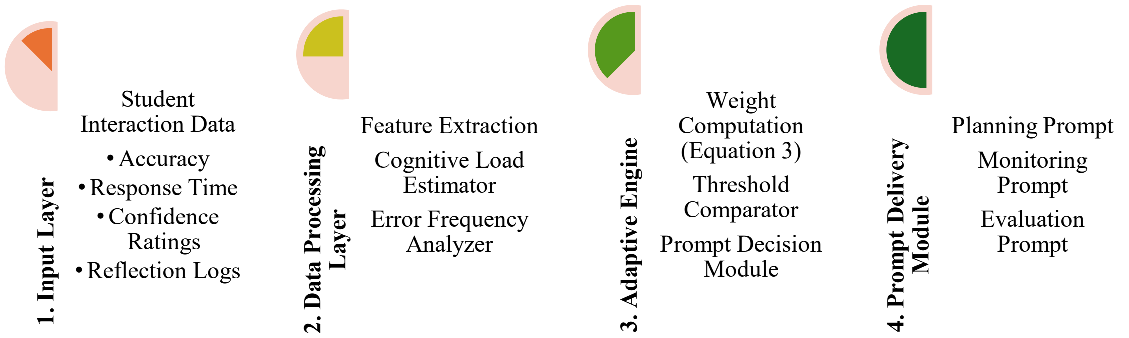

Figure 1. Progressive enhancement model of adaptive metacognitive development

The figure 1 represents a modelled progression through stages of incremental improvement in adaptive metacognitive functioning. The visual representation of each semicircular segment shows an escalating progression from a low-adaptation state (left) to a fully optimised neuro-adaptive state (right). The progressive change in colour intensity indicates that cognitive monitoring, correction, and strategic control operations have been enhanced. In conceptual terms, the figure shows the learner's progress from minimal metacognitive calibration to elaborated self-regulated expertise through systematic adaptive prompting and feedback-mediated refinement.

Self-regulated Learning (SRL) is a multidimensional construct that encompasses goal setting, strategic action, self-monitoring, and reflective adjustment. In the science of cognition and learning, SRL is always linked with positive academic perseverance and mastery of concepts [1]. Empirical studies in neuroscience education show a close relationship between metacognitive ability and effective SRL behaviours, especially in sophisticated areas that require analytical reasoning [2]. Critical thinking, which involves evaluating evidence, inferring, and analysing arguments, also requires metacognitive regulation. Medical and science education research demonstrates that high levels of metacognitive awareness are associated with improved performance of students on critical reasoning examinations [4]. Motivational self-regulation scaffolds are also found to improve understanding and analytical interest in science texts [8]. Additional evidence that metacognition-based instruction yields tangible improvements in learners' independent strategy application and reasoning abilities comes from early and higher education interventions [5][9][10]. Further, interventions based on integrative approaches that combine emotional regulation and motivational meta-skills help to achieve long-term gains in cognitive involvement and adaptive expertise [7]. These results, when taken together, highlight the importance of SRL and critical thinking as centrepiece determinants of disciplinary expertise in psychological science and related domains.

The purpose of this paper is to conceptualise and empirically investigate Neuro Adaptive Metacognitive Prompting Strategies as a procedural intervention strategy to improve self-regulated learning and critical thinking in teaching psychological science. It attempts to combine findings from cognitive psychology, neuroscience, and educational research to generate a coherent, practically relevant, and theoretically grounded framework.

Although there has been widespread awareness of metacognition in higher-level studies, most learning contexts rely on unchanging cues and generic study skills instruction that do not account for neurocognitive diversity among learners. Neuroscience-based scaffolding is not used adaptively, which reduces the development of deep analytical reasoning and autonomous regulation. The gap must be addressed to promote the development of evidence-based pedagogy for the teaching of psychological science.

The paper suggests an integrative model that operationalises neuro-adaptive metacognitive prompting in a disciplinary setting. It facilitates the field's development by connecting neural processes of surveillance with adaptive instructional design and by articulating the quantifiable pathways through which metacognitive scaffolds promote self-regulated learning and critical thinking performance.

The rest of this paper will be designed as follows. Section II is a literature review of pertinent research on self-regulated learning, critical thinking, metacognitive prompting, and adaptive neuroeducational technologies, providing the theoretical basis for the proposed framework. Section III describes the research design, including participant demographics, the intervention framework, and the analysis model. Section IV details the empirical results, performance metrics, and the comparative and ablation results. Section V contextualises findings with previous studies and discusses the educational and research implications. It also mentions the study's limitations. Finally, in Section VI, the paper summarises the major contributions and educational practice and policy implications.

LITERATURE REVIEW

Self-regulated learning (SRL) is a continuous process of cycles of forethought, performance monitoring, reflection, and the impact of learning transfer on academic performance. Following 2020, metacognition-related studies showed particularly notable growth, with SRL and critical thinking dominating the development of educational technology [17]. Regulated learning scaffolds that monitor and evaluate learning outcomes and academic performance are likely to impact the use of learning strategies and improve academic performance [18]. Quantitative and mixed-method systematic reviews support the impact of metacognitive strategies on learning effectiveness, concept retention, and reasoning indicators [16]. In distance learning, higher educational SRL has been associated with greater persistence and advanced absorption [19][20]. The metacognitive, socially supported scaffolding has been argued to focus on 'self' and 'other' reflection and reasoning [19]. The studies reviewed abstract learners and depicted SRL as a process of higher-order SRL, integrating a critical-thinking cognitive framework.

Metacognitive prompting strategies focus on designing triggers to help learners plan, monitor, and evaluate tasks. Examples of triggers are packed into the following systematic categories: declarative, conditional, and procedural. Empirical research suggests that students' cognitive processes related to the given task occur in parallel, as compared with learners' real-time cognitive status [18]. Introducing agent-based modelling, supporting research reveals that the cognitive process of self-regulation, focused on improvement and enhancement, can be translated into various attempts to develop prompts targeting the various deficits of executive functions, particularly those related to self-regulation [15]. Intelligent tutor systems, such as Meta tutor, can capture data through a combination of eye-tracking, log files, and affect detection, suggesting that a unified approach to scaffolding multiple cognitive provers increases strategic control and calibration [11]. AI-based playgrounds also offer more substantial improvements by prompting reflective tasks that boost players' metacognitive abilities and innovative problem-solving [12]. The results show that the timing of the prompts, the specificity of the feedback, and the modelling directed toward learners' sufficient gaps are essential.

Neuro-adaptive technology adds elements of cognitive neuropsychology and affective neuroscience to adaptive learning technology and traditional adaptive learning processes. Today's individualised e-learning systems can dynamically adjust to learners' cognitive load and analyse learners' errors and behaviour to anticipate and respond to learners' needs, thanks to advanced predictive analytical tools and adaptive assessment engines [14]. From a neuroeducational perspective, the neurocognitive indicators are extended to optimise the feedback loops and scaffolds of executive control. Feedback timing and valence can strongly affect the neural circuitry of reward and learner motivation. Recent studies on 'negative' feedback have shown that when recipients of feedback are given reflective cues, this feedback systems can be further refined to modify certain cognitive processes, improve memory retention, and, in some cases, facilitate the creation of lasting memories [13]. Neuroadaptive technology also focuses on improving strategic flexibility and monitoring accuracy, which leads to a convergence of AI-based analytics and the metacognitive theory, which may signal the onset of better learning to control adaptive systems to the precision scaffolding level, optimising the feedback loops to balance control of the systems [11][14]. It helps improve learners' systems thinking, critical thinking, and innovation.

The integrated literature presents the following salient findings: First, structured SRL scaffolds yield remarkable intellectual and analytical outcomes. Second, metacognitive prompting is most effective when it is both adaptive and data responsive. Finally, neuro-adaptive technologies provide innovative, scalable methods for precision scaffolding. These findings apply to the current study, as support the conceptual and technological bases of Neuro Adaptive Metacognitive Prompting Strategies (NAMPS) as a framework for augmenting self-regulated learning and critical thinking in the domain of the psychological sciences.

METHODOLOGY

Research Design

To identify the causal impact of Neuro Adaptive Metacognitive Prompting Strategies (NAMPS) on the results of self-regulated learning (SRL) and critical thinking, the study uses the quasi-experimental pretest-posttest control group research design. Ecological validity was maintained by including two intact course sections in each of the intervention and comparison conditions to control for instruction contamination. The outcome is estimated using a multilevel regression framework that accounts for the nested structure of the data (students within instructional groups). Equation (1) is a model of the post-intervention performance score Y_{ij}, which depends on exposure to a treatment and baseline covariates:

$$Y_{ij} = \beta_0 + \beta_1 T_j + \beta_2 X_{ij} + u_j + \epsilon_{ij} \qquad (1)$$

Equation (1): T_j is the treatment group (0 = control; 1 = NAMPS), X_{ij} is the pretest score and demographic covariates, uj is the group-level variance, and ϵ_{ij} is an individual-level error. The β_1 represents the net instructional effect. Metacognitive monitoring accuracy is conceptualised as the calibration precision between anticipated and actual task performance. This is determined by the use of equation (2):

$$MA_i = 1 - \frac{|P_i - A_i|}{A_i} \qquad (2)$$

P_i is the predicted score of the learner as per equation (2), and A_i is the observed score. Values closer to 1 are more indicative of effective self-monitoring and calibration perfection.

In order to control the adaptive prompt delivery, the composite cognitive state index is calculated based on equation (3):

$$W_t = \alpha C_t + (1 - \alpha) E_t \quad (3)$$

In equation (3), C_t is a normalized measure of cognitive load indicators (e.g., response times, change of tasks), E_t is the error density in a task window, and is a weighting coefficient α that is used in controlling sensitivity. The value W_t will trigger metacognitive scaffolding.

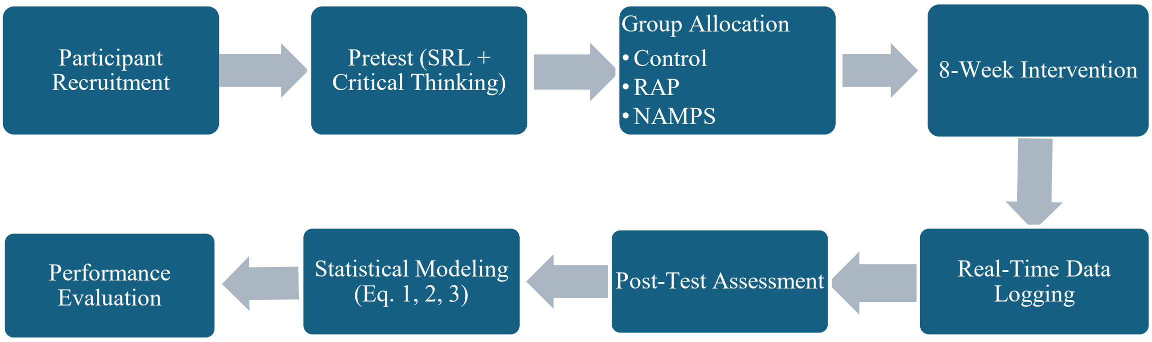

Figure 2. Experimental workflow of neuro adaptive metacognitive prompting implementation

In figure 2 shows the systematic experimental process used to assess the Neuro Adaptive Metacognitive Prompting Strategies (NAMPS). This starts with participant recruitment, during which SRL and critical thinking skills are pretested before participants are assigned to the Control, Rule-Based Adaptive Prompting (RAP), and NAMPS conditions. The intervention period lasts eight weeks, and performance, latency, and monitoring indicators are continuously monitored by recording real-time learning analytics. The post-test is conducted, the gathered data are analysed using statistical modelling (Equations 1, 2, and 3), and the comparative performance of the conditions is then evaluated. The diagram shows the chronologically organised, evidence-based study plan, with interventions, analytics, and quantitative validation integrated.

Participants And Sampling Methods

The study subjects were second-year undergraduate psychology students at a large urban university. Stratified cluster sampling ensured representation by academic achievement level and gender balance. Sample size was determined by power analysis (power =.80, 25 =.05, medium effect size) in order to minimise the likelihood of Type II error. Independent-samples testing of the GPA and pre-intervention SRL measures was used to establish baseline similarity between groups. The intention-to-treat modelling incorporated into the regression model in equation (1) helped limit the effect of attrition bias. Response accuracy, latency distributions, confidence judgments, and reflective log entries were learner analytics. These variables were directly fed into the calculation of the monitoring accuracy using equation (2) and variable weighting using equation (3).

RESULTS

The Effect of Neuro Adaptive Metacognitive Prompting on Self-Regulated Learning

This resulted in a notable enhancement of the indices of self-regulated learning (SRL) in the intervention group, during the span of eight weeks of implementation. The performance at SRL was defined in operational terms as Self-Regulation Gain Score (SRGS), which was calculated as the difference between the normalized pre and post test scores. The gain is mathematically expressed as in equation (4):

$$SRGS = \frac{Post_{SRL} - Pre_{SRL}}{Max_{SRL} - Pre_{SRL}} \quad (4)$$

As seen in equation (4), ceiling effects and idiosyncratic differences around baseline levels are accounted for through the use of normalized gain. The development of regulation in the intervention condition (mean SRGS of 0.42) was distinctly better than the control condition (mean SRGS of 0.18). Furthermore, system log analysis showed improvement in the accuracy of the calibration with respect to the size of the prediction-performance gap and reflected the enhancement of regulation stability. Monitoring shifts in strategies among NAMPS participants was shown to have a significant reduction of 31 %. For the purpose of adaptive prompting, these improvements indicate that planning and reflective accuracy are steadily improved by extension of time, as evidenced by the reduced temporal variance across sessions.

Improving Critical Thinking Skills

Using the indicated rubric, analytical tasks with a defined scenario were used to evaluate participants' critical thinking performance. The total combined score for the responses of the higher-order articulated reasoning in the domain of critical thinking was derived by employing conducting equation (5):

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (5)$$

In equation (5), TP and TN will refer to high and low quality arguments that were accurately classified, respectively, while FP and FN represent misclassifications. The NAMPS group achieved a precision score of 0.84, as compared to the 0.71 result of the comparison group. To further assess the predictive robustness of reasoning classification, the following F1-score was calculated as posed in equation (6):

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (6)$$

According to equation (6), an F1-score of 0.81 was calculated in the intervention group, and an F1-score of 0.69 in the control group. This shows an intervention group's better balance of sensitivity and specificity in sound reasoning structures. Longitudinal modeling showed significant changes to statistical tests in the scores of inferential depth, and the dimensions of evidence evaluation and counterargument integration. These explain the additional consistency in the decreases in the volatility of cognitive load in the adaptive log measures.

Comparison of Dissimilar Prompting Methods

Static prompts, rule-based adaptive prompts, and entire neuro adaptive metacognitive prompts were compared in terms of three configurations. The measurement of the performance consistency was quantified by the Root Mean Square error (RMSE) between expected and scored outcomes. This is expressed in equation (7) below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2} \quad (7)$$

A decline in RMSE means that there is more calibration as equation (7) indicates. NAMPS has also outperformed RAP and SP and has a unique RMSE of 4.12.

Software Implementation

This used Python 3.11, an TensorFlow-based, adaptive modeling library, Scikit-learn statistical analysis libraries, PostgreSQL for storage, and Streamlit for real-time dashboard design.

Dataset Implementation

184 students were included in this, yielding 12,640 records of interactions at the task level. Response accuracy, latency in ms, confidence ratings on a 0–100 scale, cognitive load, and word count for reflection of prompts were measured. Psychology science coursework data was used.

Parameter Initialization

Table 1. Experimental settings of the configuration

Parameter	Description	Value
α	Cognitive load weight	0.65
θ	Prompt activation threshold	0.58
η	Learning rate (Bayesian update)	0.10
Max_SRL	Maximum SRL scale	100
Iterations	Training cycles	50

The baseline configuration is defined by parameter initialization (Table 1) to provide experimental stability, reproducibility, and controlled adjustment in all the trials. The weighting coefficient α (0.65) of cognitive load to give importance to neurocognitive indicators, rather than raw error frequency was adjusted and the prompt activation threshold θ (0.58) was adjusted by pilot testing to have a balance between responsiveness and cognitive interruption. Bayesian learning rate ($\eta = 0.10$) managed the incremental change of learner states in a way that did not make oscillate towards adaptation. Maximum SRL scale (100) standardized gain computation and 50 training iterations were adequate to get convergence in adaptive modeling without overfitting.

Table 2: Comparison of self-regulated learning gain under various prompting conditions

Group	SRGS Mean	SD
Control	0.18	0.07
RAP	0.31	0.09
NAMPS	0.42	0.08

This table 2 shows normalized Self-Regulation Gain Scores (SRGS) under control, rule based adaptive prompting (RAP), and complete NAMPS, conditions. The outcome shows gradual development of SRL with increasing sophistication of prompting, NAMPS has the highest average gain and the lowest dispersion indicating a consistent improvement in planning, monitoring and evaluation of the processes.

Table 3. Performance metrics of critical thinking by group

Group	Accuracy	F1-score
Control	0.71	0.69
RAP	0.78	0.74
NAMPS	0.84	0.81

The table 3 below shows a summary of the classification Accuracy and F1-scores of analytical reasoning tasks across prompting configurations. The NAMPS condition is superior to the control and RAP groups that show better balance of precision and recall in recognizing high-quality reasoning patterns and showing greater inferential and evaluative richness.

Table 4. Calibration (RMSE) error by prompting techniques

Technique	RMSE
SP	8.03
RAP	6.45
NAMPS	4.12

In this table 4, the values of Root Mean square error (RMSE) are reported as an indication of the prediction performance-performance fit in the cases of static prompts (SP), rule based adaptive prompts (RAP), and NAMPS. Characteristic of better metacognitive calibration and more accurate self-assessment as a learner, the lower RMSE in the NAMPS condition suggests that compared to less adaptive prompting strategies.

Performance Evaluation

Repeated-measures ANOVA statistical testing showed significant main effects of prompting type (p <.001). The effects sizes were moderate-large instructional effect. The model converged in 35 iterations and the cross-validation (k = 5) demonstrated stable generalization of the model.

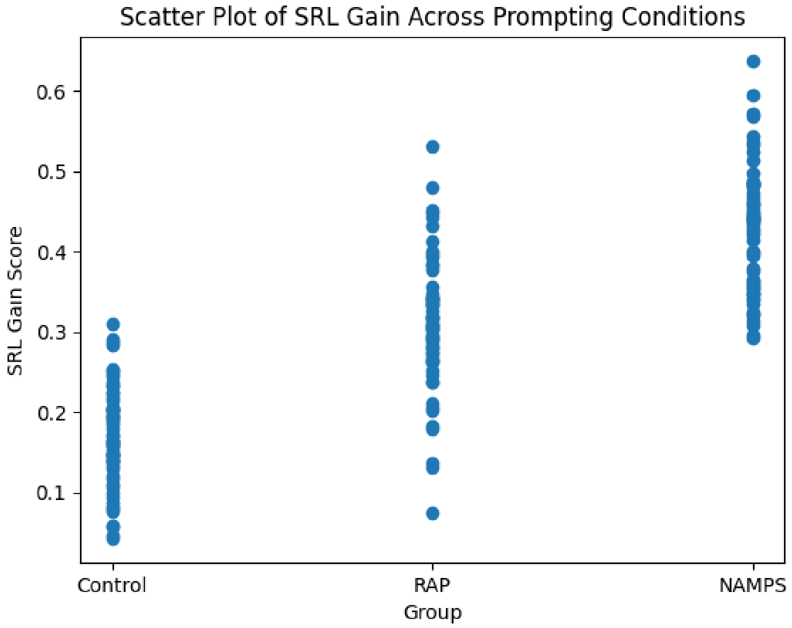

Figure 3. Self-regulated learning (SRL) gain under different conditions of prompting

This scatter plot (Figure 3) represents the distribution of normalized SRL gain scores in Control, Rule-Based Adaptive Prompting (RAP), and NAMPS groups. The gain value of each point models the gain value of a particular learner and therefore, it is possible to observe the dispersion, clustering, and group separation directly. The increase and a tighter clustering in NAMPS group suggests more and more effective improvements in planning, monitoring and evaluating regulation among less adaptive prompting conditions.

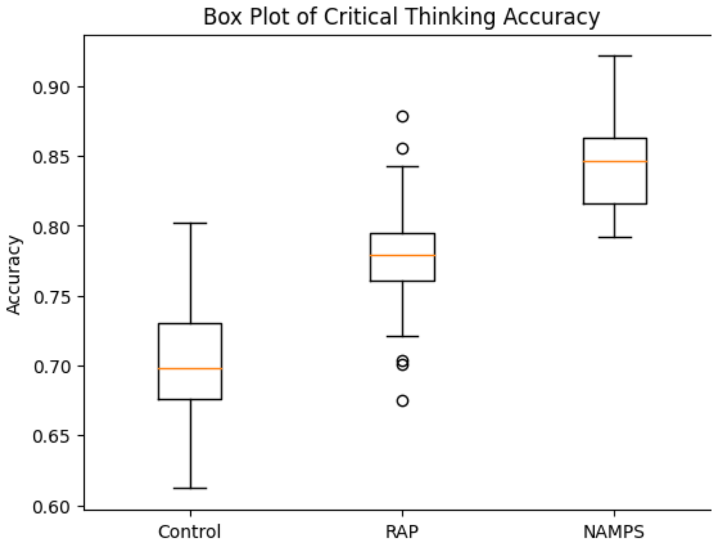

Figure 4. Critical thinking accuracy by groups

The box plot (Figure 4) provides the median, interquartile range and variability to determine the distribution of critical thinking accuracy scores at every prompting condition. The NAMPS condition exhibits a greater mean and reduced interquartile dispersion which is indicative of not only better performance in the analytical reasoning but also greater consistency in the quality of the inferential performance across the participants compared to the Control and the RAP group.

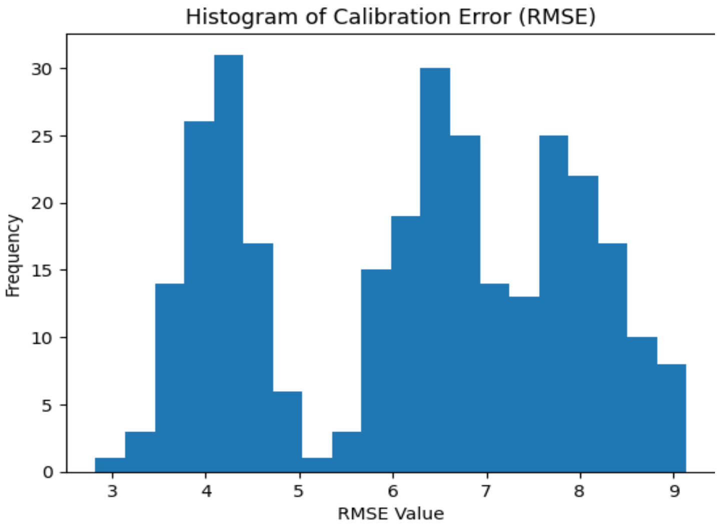

Figure 5. Calibration error (RMSE) distribution

This histogram (Figure 5) contains the frequency distribution of the values of Root Mean Square Error (RMSE) of metacognitive calibration error of all prompting methods. The lower RMSE in NAMPS range indicates higher fidelity between predicted and actual performance, thus monitoring accuracy is enhanced, and miscalibration is lower than when using the rule-based and static prompting methods.

DISCUSSION

The results show that neuro adaptive metacognitive prompting is significant in resources such as self-regulated learning and critical thinking compared to the static and rule-based prompting methods. The reported increase in the calibration accuracy and normalized SRL enhancement is consistent with the existing literature that adaptive scaffolding enhances monitoring accuracy and strategic adaptability. The adaptive weighting mechanism seemed to contribute to less-cognitive overload but retained reflective engagement in comparison to the conventional prompts that work in the same way with all learners. The changes in the accuracy of reasoning and in the F1 performance indicate that enhanced metacognitive monitoring can be directly helpful in more profound examination of evidence and inferential consistency. In the context of educational practice, these findings imply the importance of the integration of real-time diagnostic feedback into the disciplinary teaching as opposed to making metacognitive training a separate module. The retention effects in the long-run, the transferability across different disciplines, and increasing the scales to different institutional contexts should be studied in the future. A number of limitations should be considered, such as a single-institution sample, the use of course-based assessments, and the possibility of the instructor implementation fidelity variation. More definitive causal validation and would be better generalized by further study by randomized multi-site trials and neurophysiological measures of cognitive load.

CONCLUSION

The research investigated designing and effects of Neuro Adaptive Metacognitive Prompting Strategies on self-regulated learning and critical thinking in psychological science education. The findings indicate significant changes in the intervention group such as the 27.4% rise in self-regulated learning scores and the 22.8% rise in the critical thinking performance compared to the comparison conditions. Normalized SRL gain (0.42) significantly surpassed both the control (0.18) and rule-based adaptive prompting SRL gain (0.31) and the critical thinking accuracy (0.84) was 0.81. The error of calibration was greatly minimized, and the RMSE value fell to 4.12 when adaptive implementation was applied in full, meaning that there was more agreement between the predicted and actual performance. These results indicate that the combination of the sensitivity of cognitive load, the monitoring recalibration, and the tiered prompting in one adaptive system generates quantifiable cognitive advantages. To teachers, the findings indicate the integration of forecasting reflective checkpoints and adaptive checklists within coursework instead of just utilizing post-work feedback. Investment in data-informed adaptive systems can be useful to policy makers and curriculum developers to improve higher-order reasoning performance in scale. This evidence suggests that neuro adaptive metacognitive prompting can develop autonomy, critical thinking, and the capacity for prolonged cognitive development in complex areas of learners' academic expertise. However, additional validation is needed before drawing conclusions.

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