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Research paper

Integrating Metacognition and Structured Problem-Solving in Physics: Effects of the e-GraVT Digital Module on Secondary Physics Students

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ABSTRACT

Amid global efforts to strengthen STEM education, Physics remains challenging due to abstract topics like gravitation. Many secondary students struggle with conceptual understanding, systematic problem-solving and metacognitive regulation. This study examined the impact of the e-GraVT Module, a digitally delivered, metacognitively oriented intervention on students' metacognitive and physics problem-solving skills. A quasi-experimental design involved 99 Malaysian Form Four students, divided into treatment and control groups. Metacognition was assessed via the Physics Metacognition Inventory, while problem-solving was evaluated using the MAPS rubric. Analyses of Covariance (ANCOVA and MANCOVA) were conducted to control for baseline differences. Findings indicated that the treatment group achieved significantly higher post-test levels of metacognitive knowledge and regulation than the control group, alongside substantially greater overall problem-solving performance. At the indicator level, large effect sizes for Useful Description and Specific Application of Physics suggest strong gains in constructing meaningful problem representations and applying appropriate concepts in context. These results suggest that embedding metacognitive prompts, graphical–verbal scaffolds, and structured conceptual procedures within a digital module may foster higher-order thinking, improving problem-solving sophistication and core STEM competencies. This study highlights the potential of technology-enhanced metacognitive instruction in addressing persistent learning difficulties in secondary physics.

Keywords: metacognition, problem-solving, STEM education, e-GraVT digital module, Conceptual Understanding Procedures (CUP)

STEM (science, technology, engineering, and mathematics) education is a core driver of Malaysia's socio-economic development. It is central to national aspirations of becoming a high-income, technologically advanced country by producing a highly skilled workforce for high-technology industries while nurturing innovation, creativity, and informed citizenship (Mcdonald, 2016). Through STEM education, students are expected to develop critical and creative thinking skills that enable them to address complex social and environmental problems and to engage meaningfully with contemporary scientific and technological issues (Margot & Kettler, 2019). In particular, STEM education is seen as critical for promoting the acquisition of skills, knowledge, and competencies that contribute to the creation of climate change and sustainability solutions among secondary school students (Grimalt-Álvaro et al., 2025). Despite sustained policy emphasis and recent increases in STEM enrolment, Malaysia still falls short of the 60:40 STEM to non-STEM target; in 2024, upper secondary STEM enrolment was 50.83%, only about a 10% improvement over 2019 (Ministry of Education

Malaysia, 2024). National and international assessments further show that students' scientific literacy and higher-order thinking remain below desired levels (OECD, 2023; TIMSS National Report, 2020).

Within this ecosystem, Physics occupies a pivotal position. It provides conceptual and mathematical tools that underpin advances in engineering, information and communication technology, medical imaging, energy systems, and aerospace (Purzer et al., 2015). Success in school Physics, therefore, functions as a gatekeeper to high-impact STEM pathways. Yet national data are concerning, although overall STEM enrolment has risen, the number of students choosing core STEM subjects, including Physics, for Sijil Pelajaran Malaysia (SPM) has declined. For Physics, candidate numbers fell by 1.42% between 2022 and 2023 (1,306 fewer students), and only 24% of the 2023 SPM cohort took Physics (Ministry of Science, Technology and Innovation, 2024). Performance is polarized, while the mean subject grade point improved slightly; only 26.9% obtained A+, A, or A–, most performed at a moderate level (B+ to C), and 0.6% failed (Malaysian Examination Board MOE, 2024).

Research attributes these patterns to perceptions of Physics as difficult, abstract, and mathematically demanding (Guido, 2018), compounded by weak mathematical foundations (Ariani, 2020). Malaysian studies report that students struggle to master conceptual Physics, rely on rote memorization, and show weaknesses in structured, multi-step problem solving (Makhtar et al., 2021). Salmiza (2012) found that many students cannot apply Physics concepts accurately in daily life. PISA and TIMSS results, consistently below the OECD average and TIMSS centre-point of 500, corroborate these concerns, suggesting inadequate conceptual understanding and higher-order thinking (Mazana et al., 2018; Yee et al., 2017).

Beyond content and procedural difficulties, metacognitive skills contain students' awareness and regulation of their own thinking and are critical for Physics learning (Zohar & Barzilai, 2013). Stronger metacognitive knowledge and regulation enable students to select appropriate strategies, detect inconsistencies and revise reasoning in complex Physics problems (Al-Abdullatif, 2020). However, many secondary students show low metacognitive engagement, seldom planning, monitoring, or evaluating their solutions systematically (Ntobeko, 2018). This lack of metacognitive scaffolding in traditional, teacher-centred instruction hinders self-regulated learning (Whitcomb et al., 2021).

These metacognitive weaknesses are intertwined with deficits in Physics problem-solving. Problem-solving in Physics requires interpreting context, activating concepts, constructing representations, and formulating solution plans, not just formula application. Students often struggle with non-routine problems and integrating conceptual understanding with systematic strategies, particularly in topics like gravitation. The MAPS (Minnesota Assessment of Problem Solving) indicators highlight weaknesses in problem representation and evaluation, stages heavily reliant on metacognitive regulation.

Traditional approaches often fail to foster higher-order thinking and metacognitive skills (Mafarja et al., 2022). While digital tools offer promise, few existing modules for secondary Physics gravitation explicitly integrate structured problem-solving frameworks with metacognitive scaffolding (Schumacher & Ifenthaler, 2021). There is a clear need for interventions that bridge conceptual knowledge, procedural application and self-regulated learning.

Therefore, this study investigated the effectiveness of the e-GraVT module, a digitally delivered learning intervention grounded in the Conceptual Understanding Procedures (CUP) model, in enhancing upper secondary students' metacognitive and Physics problem-solving skills in gravitation. The e-GraVT module aims to strengthen conceptual understanding and embed explicit metacognitive prompts and scaffolds aligned with CUP and MAPS indicators, supporting planning, monitoring, and evaluating problem-solving approaches.

Specifically, the study addressed:

1. Does the e-GraVT module improve students' metacognitive knowledge and regulation compared to conventional instruction?
2. Does the e-GraVT module enhance students' Physics problem-solving skills overall and across the five MAPS indicators compared to conventional instruction?

This quasi-experimental study, comparing e-GraVT module with conventional instruction, aims to provide new insights into metacognitively-oriented digital modules in secondary Physics education, addressing students' metacognitive needs and strengthening problem-solving skills in gravitation.

THEORETICAL FRAMEWORK

Metacognition in physics learning and problem-solving

A growing body of work highlights metacognition, which is students' awareness and regulation of their own thinking as critical to conceptual understanding and problem-solving in Physics. Metacognitive skills such as planning, monitoring, and evaluating learning correlate positively with motivation, conceptual comprehension, and performance (Balta & Awedh, 2017; Chong & Sungap, 2021; Dessie et al., 2024). Conceptual understanding provides the structural foundation of Physics learning (Tso et al., 2022), while metacognitive regulation helps learners select strategies, check understanding, and revise misconceptions (Hernández-Suarez et al., 2022; Schraw & Dennison, 1994; Prihatmojo et al., 2026).

Metacognition comprises two main components: knowledge of cognition (awareness of one's own thinking processes, strengths, weaknesses, and available strategies) and regulation of cognition (the ability to plan, monitor, and evaluate one's learning and problem-solving activities). Conversely, weak metacognition leads students to overestimate understanding and persist with ineffective approaches (Morphew et al., 2020; Taasoobshirazi et al., 2015). Therefore, explicit support for metacognitive development is essential in Physics education, particularly in abstract and mathematically intensive topics such as gravitation.

Conceptual understanding procedures (CUP) and structured problem-solving

The Conceptual Understanding Procedures (CUP) model explicitly integrates conceptual understanding with step-by-step problem-solving procedures (Gunstone et al., 1999). Mastery requires coordinating multiple representations and multi-step quantitative reasoning. The CUP model has been shown to deepen understanding, support systematic problem-solving, and stimulate metacognitive awareness (Carpendale & Cooper, 2021; Nurlina et al., 2020). The CUP model typically comprises three learning phases:

1. Individual phase: Students engage with activities that elicit and refine their conceptual understanding of key ideas.
2. Group discussion phase: Students work through guided problem-solving tasks that require them to apply concepts using explicit, step-by-step procedures.
3. Presentation phase: Students articulate their reasoning, justify their choice of formulas, and evaluate the reasonableness of their answers through reflection questions and metacognitive prompts.

By structuring learning in this way, the CUP model encourages students to move beyond rote memorization and procedural fluency toward deeper conceptual engagement and self-regulated learning. However, most implementations of CUP have been paper-based (Gunstone et al., 1999) and few have been integrated with digital technology to enhance accessibility, interactivity, and metacognitive scaffolding.

Cognitive load theory and digital learning environments

Cognitive Load Theory (CLT) posits that learning is optimized when instructional design manages the cognitive demands placed on working memory (Sweller, 1988; Koçak et al., 2015). Complex Physics concepts, such as Newton's Law of Universal Gravitation and gravitational field strength, impose high intrinsic cognitive load. Effective instruction should minimize extraneous load (irrelevant information or poorly designed materials) and support germane load (processes that contribute to schema construction and automation).

Digital learning environments offer unique affordances for managing cognitive load and enhancing Physics learning through interactive, multimodal experiences, simulations, and feedback (Bedenlier et al., 2020; Muzi et al., 2021). The Cognitive Theory of Multimedia Learning (Mayer, 2014) further suggests that learning is enhanced when information is presented through both verbal and visual channels (dual-channel processing), when extraneous material is excluded (coherence principle) and when essential information is highlighted (signalling principle).

In addition, constructivist and social constructivist perspectives emphasize that learners actively construct knowledge through interaction with materials, peers, and teachers rather than passively receiving information. Digital modules can support constructivist learning by providing opportunities for exploration, collaboration, and reflection, while also offering individualized pathways and immediate feedback.

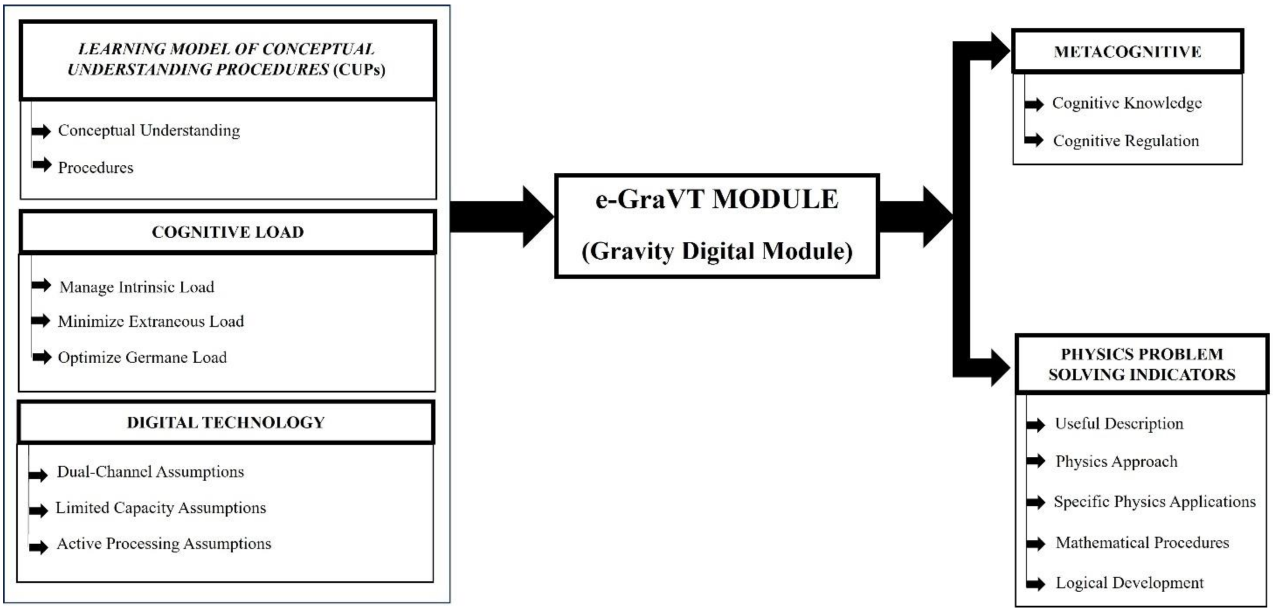
However, few digital resources for secondary Physics are explicitly structured around metacognitive regulation or integrated with the CUP model and classroom-based metacognition research in secondary Physics, especially on gravitation, remains limited (Avargil et al., 2018; Daher & Hashash, 2022).

Conceptual framework for the e-GraVT module

In response to the need for instructional approaches that simultaneously foster conceptual understanding, metacognition, and problem-solving in gravitation, the e-GraVT module was developed. The module integrates the CUP model with principles from Cognitive Load Theory and multimedia learning, delivered through a digital platform to enhance accessibility, interactivity, and metacognitive scaffolding. Figure 1 presents the conceptual framework underpinning the e-GraVT module.

Figure 1

Conceptual framework for e-GraVT module



As shown, the module is grounded in three theoretical pillars:

a. Active Student-Centred Learning Model – Conceptual Understanding Procedures (CUP): The module follows the CUP phases (individual, group discussion, presentation, and an added self-reflection phase) to promote conceptual understanding and procedural fluency.
b. Cognitive Load Theory (Cognitive Load): The design manages intrinsic load by breaking complex gravitation concepts into manageable sub-concepts, reduces extraneous load through clear visuals and step-by-step explanations (Manage Intrinsic Load, Minimize Extraneous Load), and optimizes germane load to support schema construction (Optimize Germane Load).
c. Digital Technology: The module leverages dual-channel processing (Dual-Channel Assumptions), limited capacity (Limited Capacity Assumptions), and active processing (Active Processing Assumptions) principles from multimedia learning theory to present content through text, narration, animations, and diagrams.

These three pillars converge in the e-GraVT Module (Gravity Digital Module), which is designed to enhance two key outcomes:

i. Metacognition: Comprising cognitive knowledge and cognitive regulation.
ii. Physics Problem-Solving: Comprising a useful description, physics approach, specific application of physics, mathematical procedures, and logical progression.

By embedding metacognitive prompts, graphical-verbal scaffolds, and step-by-step CUP procedures within a digital environment, the e-GraVT module aims to support students in becoming more aware of their thinking processes, more strategic in their problem-solving approaches, and more capable of constructing coherent mental models of gravitational phenomena.

Rationale and research gaps

Despite the documented benefits of metacognitive instruction, structured problem-solving frameworks, and digital learning environments, few studies have developed and empirically evaluated digital modules that explicitly integrate all three elements, which are metacognitive scaffolding, the CUP model, and multimedia design principles, within the context of secondary-level Physics gravitation. This gap is particularly significant given the persistent difficulties students face with gravitation (Hisham, 2023; Norbaizura, 2019; Prescott et al., 2024; Syuhendri, 2019) and the limited availability of evidence-based digital resources tailored to this topic.

The e-GraVT module addresses this gap by providing a theoretically grounded, empirically testable intervention designed to enhance both metacognitive and Physics problem-solving skills. The present study evaluates the effectiveness of this module in a real-world classroom context, contributing to the literature on technology-enhanced metacognitive instruction in STEM education.

RESEARCH METHODOLOGY

Research design and participants

The study employed a quasi-experimental design using five intact classes (N=99) from two secondary schools. The treatment group consisted of three classes (n=58), while the control group comprised two classes (n=41). To ensure instructional consistency and minimize teacher bias, five experienced physics teachers (one for each class) were involved in the study. Before the intervention, all teachers attended a standardization briefing to ensure that the learning objectives, content coverage, and instructional protocols were applied consistently across both groups.

This study was conducted from May to July 2025. The study focused on a population of Form Four students taking Physics in the pure science stream in the Alor Gajah district, Melaka. This district was selected because the Grade Point Average (GPMP) for Physics in the Sijil Pelajaran Malaysia (SPM) results from 2022 to 2024 was among the lowest compared to other districts in Melaka.

Instruments

This study uses two instruments to answer the research questions, namely the Physics Metacognition Inventory and the Physics Problem Solving Skills Test. Metacognition was measured using the Physics Metacognition Inventory, consisting of 26 items, as shown in **Table 1** adapted from the questionnaire developed by Taasoobshirazi et al. (2015) to assess students' metacognition in solving Physics problems.

Table 1

Physics metacognitive inventory (PMI) questionnaire

Main component	Sub-component	Item numbers	Total items
Cognitive knowledge	Knowledge about cognition	5,6,7,11,12,13	6
Cognitive regulation	Planning	4,10,18,23	4
	Monitoring	2,15,16,21	4
	Evaluation	8,9,17,25	4
	Debugging	3,22,26	3
	Information management	1,14,19,20,24	5
	Total items		26

Students respond to each item using a five-point Likert scale ranging from 1 (never true of me) to 5 (tend to be true of me). The scoring is interpreted according to mean values, with 1.00–2.33 indicating a low level, 2.34–3.66 a moderate level, and 3.67–5.00 a high level of metacognitive skills, as referenced from Yifan et al. (2026).

Physics problem-solving skills were measured using the Physics Problem Solving Skills Test, which comprised four Physics questions on the Gravitation chapter, specifically Newton's Law of Universal Gravitation subtopic. Students' problem-solving skills were scored using an adapted version of the Minnesota Assessment of Problem Solving (MAPS) rubric developed by Docktor & Heller (2009), a research-based rubric designed to assess problem-solving skills in Physics. The rubric allowed analysis of five problem-solving indicators presented in **Table 2** to suit this study.

Table 2

Description of each indicator in the adapted MAPS rubric

Indicators	Concise description
Useful Description	The descriptive indicator is useful in assessing how information is organized from the given physics problem into a meaningful summary, in the form of sentences, visuals or symbols.
Physics Approach	The physics approach indicator refers to assessing the student's selection of the correct physics concept in solving physics problems.
Specific Application of Physics	The specific physics application indicator aims to assess the process of applying or applying physics concepts and principles such as formulas and physics quantities used.
Mathematics Procedures	The mathematical procedure indicator assesses how students make the selection and use of appropriate mathematical procedures when solving physics problems.
Logical Progression	The logical development indicator is an assessment of the problem-solving process to ensure that students focus on the goal of the question, use the correct magnitude and quantity values and complete the answer in an organized manner.

Each indicator is given a score from 0 to 5. The total score for all physics problem-solving items is 100, with each indicator for each item worth 20 points. **Table 3** shows the level of students' physics problem-solving skills based on the percentage of scores obtained after answering physics questions based on research (Simamora et al., 2017).

Table 3
Level of physics problem solving skills based on score percentage

Level of physics problem solving skills	Score percentage (%)
Very Good	90 - 100
Good	80 – 89
Moderate	65 – 79
Weak	55 - 64
Very Weak	0 – 54

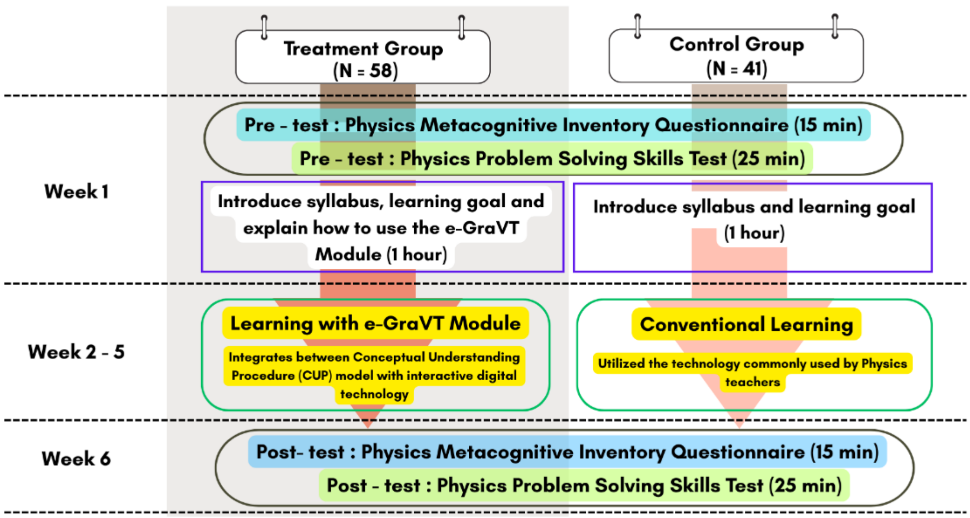
Scoring reliability

To ensure data reliability and eliminate potential researcher bias, the grading of the pre-test and post-test scripts was conducted by an independent external examiner. The appointed examiner is a highly experienced physics teacher with 15 years of expertise in the subject matter. The marking process was carried out objectively, strictly adhering to a standardized marking scheme that had been validated by a panel of experts. To maintain consistency and reliability of the scores, the external examiner followed the established marking criteria independently, without any interference from the researcher. Furthermore, a blind marking procedure was employed, where the identities of the students and their respective study groups were withheld from the examiner to ensure an unbiased evaluation. The involvement of an external subject matter expert as the sole marker serves as a quality control measure to ensure that the collected scores are valid, consistent, and free from the researcher's subjective influence.

The experimental procedure

Figure 2 outlines the quasi-experimental design comparing the treatment group (N=58) and the control group (N=41) across four phases. Both groups began with a pre-test using the Physics Metacognitive Inventory and the Physics Problem Solving Skills Test to establish baseline levels. In the first week, both groups were introduced to the syllabus and learning goals; while the treatment group received a one-hour orientation on using the e-GraVT module, the control group spent the equivalent time on an introductory session using conventional materials to ensure equal instructional time. The core instruction for both groups was then conducted over four weeks, from the second to the fifth week.

Figure 2
Experimental procedure



To ensure a fair comparison, both the treatment and control groups received the same amount of instructional time, totalling 10 hours and 40 minutes (2 hours and 40 minutes per week over four weeks). While the treatment group utilized the e-GraVT module, the control group followed conventional instruction based on the national curriculum. This conventional approach was primarily teacher-led, utilizing standard textbooks and whiteboards, supplemented by existing school-provided digital slides. Students in the control group completed the same set of gravitation problems and received teacher feedback; however, they did not have access to the explicit metacognitive prompts, graphical-verbal scaffolds or the structured CUP phases embedded in the e-

GraVT module. In the sixth week, both groups completed the post-tests to assess changes in metacognitive and physics problem-solving skills.

The e-GraVT module design procedure (intervention)

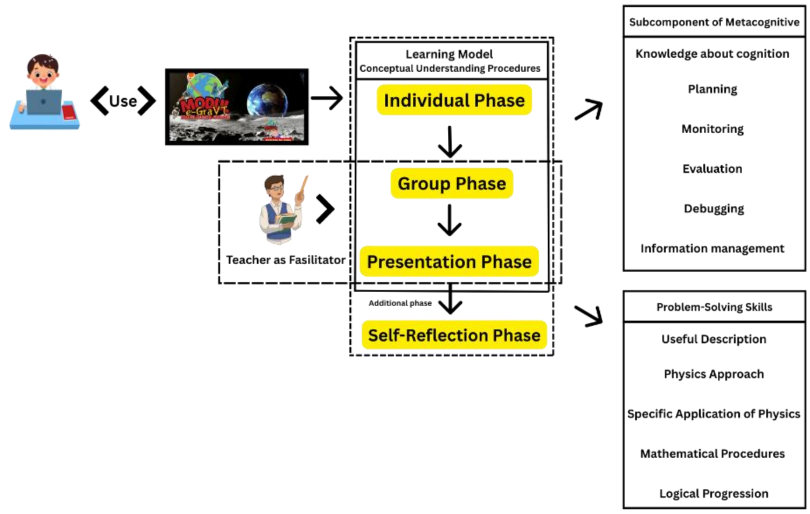
The e-GraVT module, developed via the Genially platform, targets the Gravitation chapter in the Malaysian Form 4 Physics curriculum, specifically addressing Newton's Universal Law of Gravitation (Subtopic 3.1). In addition to learning experiences built in Genially, the module is linked to Miro.com, YouTube, and the PhET Interactive Simulations application to support teaching and learning.

The instructional flow as shown in **Figure 3** is guided by the Conceptual Understanding Procedures (CUP) model, which consists of three main phases: the Individual Phase (students explore materials, answer initial questions and build foundational understanding), the Group Phase (for discussion by completing a mind map and problem solving with discuss answering questions collaboratively using Miro.com) and the Presentation Phase (groups present their discussion outcomes to the class with support from a Miro.com board). Following the Presentation Phase, an additional Self-Reflection Phase is implemented, in which students evaluate and reflect on their learning through self-rating items, metacognitive prompts (planning, drawing diagrams), and post-learning understanding checks.

When students access the module on iOS or Android devices or on a laptop, the content, collaborative activities, and assessments integrate seamlessly to support inquiry-based learning on this gravitation topic. The e-GraVT module comprises four modules: Gravitational Force, Gravitational Acceleration, Centripetal Force, and the Mass of the Earth and the Sun.

Figure 3

The instructional flow is guided by the conceptual understanding procedures (CUP) model



To ensure the fidelity of the intervention, a standardized instructional protocol was established. Each teacher in the treatment group was provided with a comprehensive teacher's guide and a fidelity checklist that outlined every activity within the e-GraVT module. The researchers conducted periodic classroom observations and held weekly brief check-ins with the teachers to verify that all phases of the Conceptual Understanding Procedures (CUP) were being implemented as intended. Furthermore, the digital platform (Genially and Miro) allowed the researchers to monitor student progress and activity completion in real-time, ensuring that the teachers were facilitating all required modules.

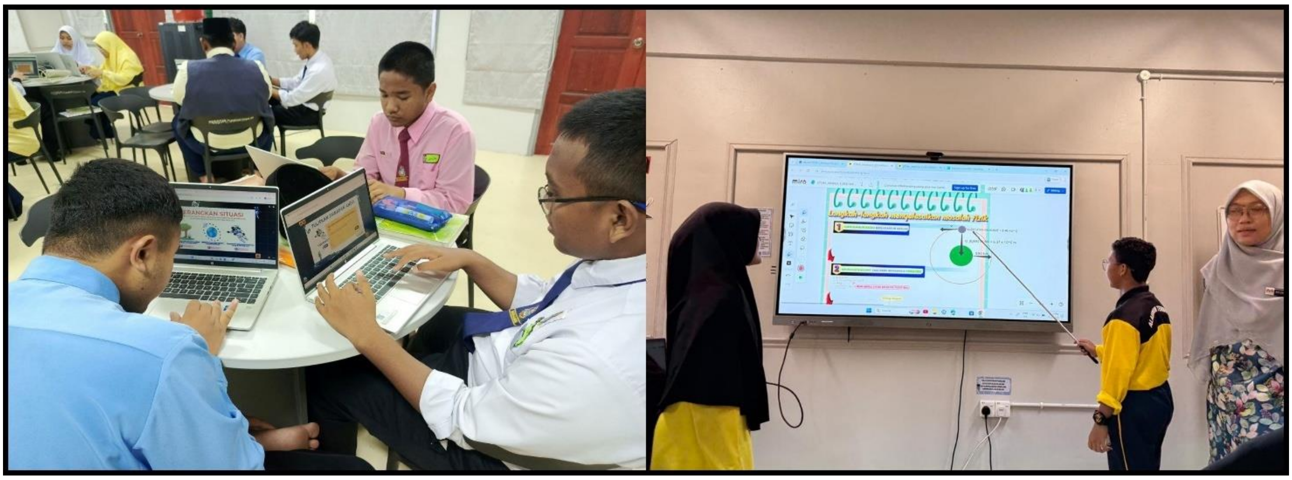
Data analysis

Data were analysed using independent-samples t-tests for preliminary group comparisons and ANCOVA/MANCOVA in IBM SPSS Statistics. For the metacognitive outcomes (overall metacognitive knowledge and regulation), a MANCOVA was first conducted with post-test scores as dependent variables, group (treatment vs. control) as the fixed factor, and the corresponding pre-test scores as covariates. Follow-up univariate ANCOVAs were then used to examine each component separately. For problem-solving performance (MAPS), one-way ANCOVAs were conducted for each MAPS dimension, with pre-test scores as covariates and post-test scores as dependent variables. Assumption checks were performed, including tests for normality of residuals (Shapiro-Wilk), homogeneity of variance (Levene's test), and homogeneity of regression slopes (interaction tests). Given the sample size (N = 99), ANCOVA is sufficiently robust to minor violations of assumptions. Adjusted means, F-statistics, p-values, and effect sizes (partial η^2) are reported.

RESULTS

The e-GraVT module, a digitally delivered learning intervention, was successfully implemented in this study. During the intervention phase, students in the treatment group demonstrated high levels of engagement and active participation, interacting dynamically with the module's features. The module served as a medium for students to navigate and solve complex Physics problems related to gravitation, guided by embedded metacognitive prompts and the structured Conceptual Understanding Procedures (CUP) framework. Students were able to iteratively apply Physics principles and refine their problem-solving strategies through the module's interactive tasks. Figure 4 illustrates student activities and engagement during the e-GraVT intervention.

Figure 4
Students learning using e-GraVT module



The module facilitated learning activities by developing both metacognitive skills through explicit self-regulation prompts and Physics problem-solving abilities via structured application of the CUP model. Following their participation in the learning process, students' metacognitive skills and Physics problem-solving skills were measured using validated instruments. The collected data were then subjected to statistical analysis for hypothesis testing. Before conducting the main analyses, preliminary data screening and assumption checks for ANCOVA and MANCOVA were performed. These included assessments of normality of residuals, homogeneity of variance, and homogeneity of regression slopes. Given the sample size (N=99) and the requirement to control for baseline differences, these parametric procedures were deemed appropriate for testing the study's hypotheses.

Effects of the e-GraVT module on metacognitive skills

Table 4 presents the descriptive statistics (means, standard deviations, and interpretation levels) for metacognitive knowledge and regulation scores for both the treatment and control groups at pre-test and post-test. To examine the impact of the e-GraVT module beyond these descriptive trends, a MANCOVA with pre-test scores as covariates was conducted, followed by univariate ANCOVAs for each component.

A MANCOVA was conducted to examine the effect of the e-GraVT module on students' metacognitive knowledge and regulation while controlling for pre-test scores. The multivariate effect of group was significant, Wilks' $\Lambda = 0.65$, $F(2, 95) = 25.26$, $p < .001$, partial $\eta^2 = .35$. Follow-up ANCOVA revealed that, after adjusting for pre-test scores, a significant difference was observed between the groups, with the treatment group demonstrating higher levels of metacognitive knowledge compared to the control group, $F(1, 96) = 36.93$, $p < .001$, partial $\eta^2 = .28$, and on metacognitive regulation, $F(1, 96) = 5.26$, $p = .024$, partial $\eta^2 = .05$.

The results of the present study are broadly consistent with these trends. Figure 5 illustrates that Form 4 students who used the e-GraVT module showed greater gains in overall metacognitive scores than those in the control group, with particularly pronounced improvements in metacognitive knowledge and information-management strategies. Cognitive regulation components such as planning, monitoring and evaluation also improved, although the effect sizes were comparatively smaller, suggesting that these regulatory processes may require longer or more intensive support.

Beyond the mean differences presented in Figure 5, the pattern of change across the two metacognitive subcomponents highlights the complementary roles of cognitive knowledge and cognitive regulation in students' learning of Physics with the e-GraVT module. In this study, cognitive knowledge refers to students' awareness of their own thinking processes, including their understanding of personal strengths and weaknesses as learners, knowledge of task demands, and familiarity with a range of learning and problem-solving strategies. Cognitive regulation, in turn, encompasses how students plan, monitor, and evaluate their thinking while engaging with Physics tasks, for example, how they set goals before solving a problem, track their understanding during solution steps, and check or revise their answers afterwards.

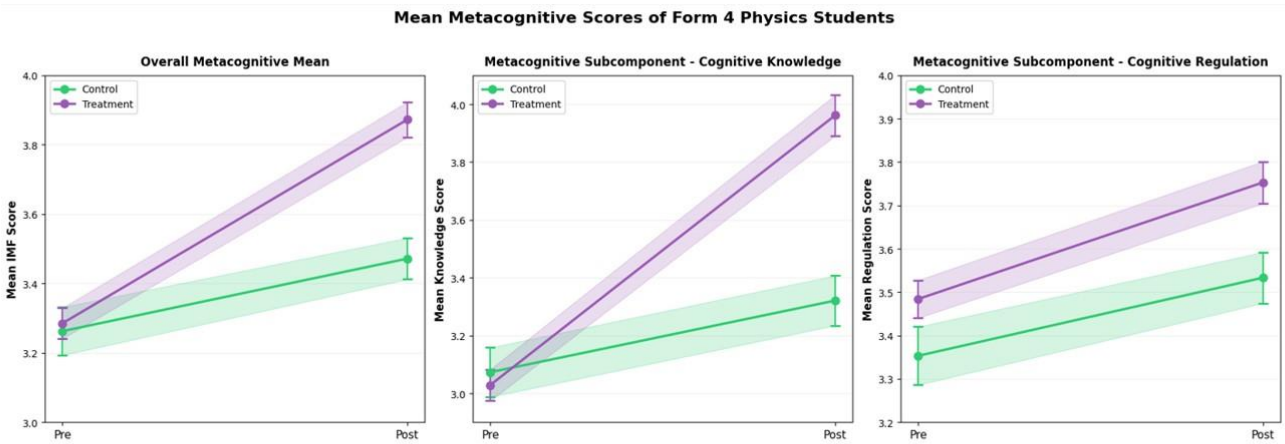
Table 4

Descriptive statistics for metacognitive skills (pre- and post-test)

Group	Component	Test	N	Mean	SD	Level
Control	Cognitive knowledge	Pre	41	3.07	0.55	Moderate
		Post	41	3.32	0.55	Moderate
	Cognitive regulation	Pre	41	3.35	0.43	Moderate
		Post	41	3.53	0.38	Moderate
Treatment	Cognitive knowledge	Pre	58	2.82	0.47	Lower
		Post	58	3.87	0.45	Higher
	Cognitive regulation	Pre	58	3.39	0.35	Moderate
		Post	58	3.87	0.40	Higher

Figure 5

Pre and post-test metacognitive scores between two groups



The finding that the treatment group moved from lower to higher levels in cognitive knowledge and from moderate to higher levels in cognitive regulation suggests that the module not only helped students become more aware of what they know about their learning but also improved how they manage and control their thinking in real problem-solving situations.

Drawing on Figure 6, the bar graph presents a comparative analysis of the mean scores for six cognitive sub-components that are Knowledge about Cognition, Information Management, Planning, Monitoring, Evaluation, and Debugging, which were measured during both pre-test and post-test phases for the treatment group.

After the implementation of the e-GraVT module, the treatment group demonstrated high levels across most cognitive components, as shown in Table 5. For cognitive knowledge, the mean score for "Knowledge about cognition" which falls into the high category. In the cognitive regulation domain, "Planning", "Evaluation", "Debugging", and "Information Management" all reached high levels as well. The only sub-component at a moderate level was "Monitoring". These results suggest that the e-GraVT module may have contributed to higher levels of students' cognitive knowledge and most aspects of cognitive regulation, with notable improvements in evaluation and planning skills. The consistent high means and relatively low standard deviations suggest that the improvement was widespread and not limited to a few individuals.

This pattern of improvement also clarifies how each metacognitive subcomponent contributes to students' readiness to regulate their own learning. Knowledge about cognition reflects students' awareness of their own learning styles, strengths, and weaknesses, and their knowledge of appropriate strategies to use when solving physics problems. For regulating cognitive components, Information Management and Planning represent students' ability to organize relevant information, select important cues or resources, set clear goals, and sequence solution steps before beginning a task. Monitoring refers to students' ongoing tracking of their understanding while they carry out the solution steps, whereas Evaluation and Debugging involve critically checking the quality of their answers, identifying errors, and correcting them.

The marked gains in Information Management, Planning, and Evaluation indicate that the e-GraVT module not only helped students understand concepts and strategies but also strengthened their capacity to manage information, plan solution pathways, and appraise the quality of their own reasoning. Although Monitoring remained at a moderate level, these findings suggest that this component may require longer exposure or additional support, while the other components were successfully raised to a high level for most students.

Figure 6

Pre-test and post-test mean scores by sub-component for the treatment group

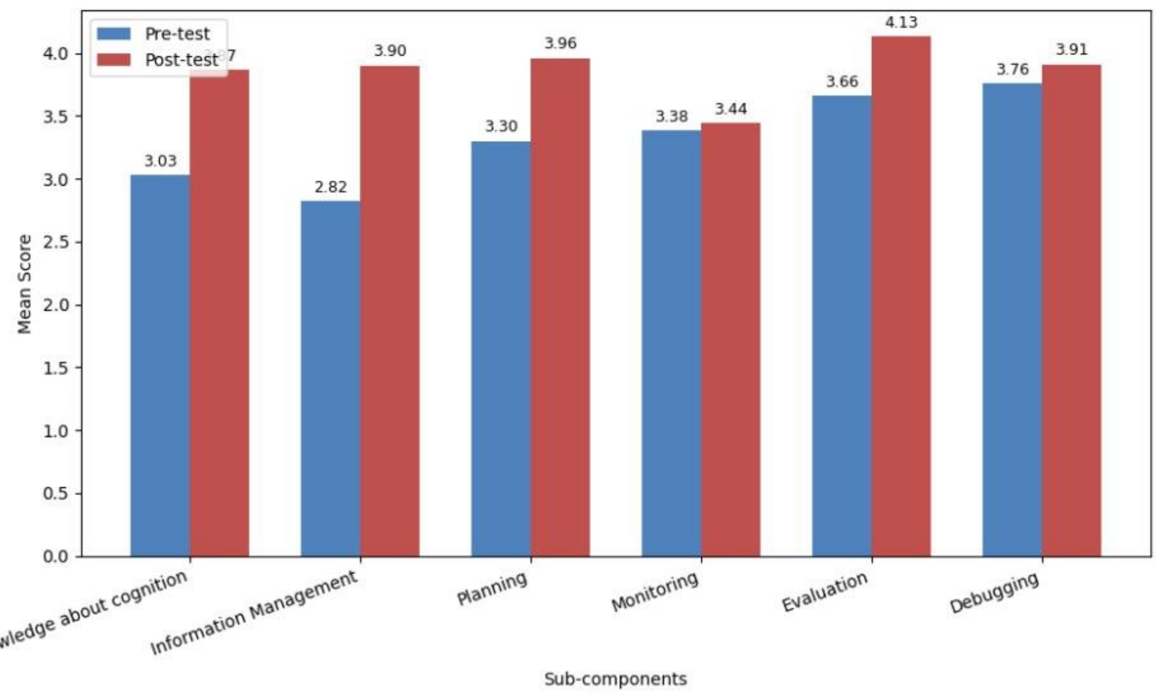


Table 5

The treatment group mean score levels across metacognitive components

Component	Sub-component	Mean	SD	Level
Cognitive knowledge	Knowledge about cognition	3.87	0.45	High
Cognitive regulation	Planning	3.96	0.54	High
	Monitoring	3.44	0.50	Moderate
	Evaluation	4.13	0.55	High
	Debugging	3.91	0.61	High
	Information Management	3.90	0.53	High

Effects of the e-GraVT Module on Physics Problem-Solving Skills

Table 6 displays the descriptive statistics (means and standard deviations) for overall Physics problem-solving skills at pre-test and post-test for both groups.

Table 6

Descriptive statistics (percentage scores)

Group	n	Pre-test mean (%) (SD)	Post-test mean (%) (SD)
Control	41	30.85 (14.30)	47.95 (17.44)
Treatment	58	20.43 (14.24)	65.26 (16.65)

To evaluate the effectiveness of the e-GraVT module while accounting for baseline differences between the treatment and control groups, a series of one-way analyses of covariance (ANCOVAs) was performed for each of the five MAPS dimensions. In each model, the post-test dimension score was the dependent variable, the instructional group (Treatment vs. Control) was the independent variable, and the corresponding pre-test score was utilized as the covariate. Preliminary diagnostics were conducted to assess the assumptions of ANCOVA. While normality and homogeneity of variance for the problem-solving dimensions were generally acceptable, tests for the homogeneity of regression slopes indicated potential interactions between the covariate and the group for some dimensions. However, given the relatively large sample size (N=99) and the practical necessity of controlling for significant baseline imbalances, ANCOVA was maintained as the primary inferential tool, with results interpreted cautiously.

As shown in **Table 7**, the ANCOVA results revealed a statistically significant effect of the e-GraVT module intervention across all five indicators of problem-solving skills after adjusting for pre-test scores. The most substantial impact was observed in Useful Description, where the treatment group achieved a significantly higher adjusted mean compared to the control group with a large effect size (partial η^2=.484). Significant treatment effects were also found for Physics Approach and Specific Application of Physics. For both indicators, the treatment group demonstrated superior adjusted post-test performance. Finally, the e-GraVT module group showed significantly higher adjusted scores for Mathematical Procedures and Logical Progression. These results suggest that the structured metacognitive scaffolding provided by the e-GraVT module effectively enhanced the quality of students' problem-solving processes across all measured indicators.

Taken together, the pattern across the five MAPS indicators suggests that the findings indicate a substantial impact in strengthening the conceptual and representational indicators of problem-solving (useful description, selection, and application of Physics concepts), while also producing moderate improvements in students' procedural and logical execution of solutions. This combination is pedagogically important, as it indicates that students were not merely learning to "do more calculations", but were developing deeper, more structured ways of thinking about Physics problems in gravitation.

Regarding the physics problem-solving indicators, **Figure 7** illustrates that the treatment group consistently achieved higher adjusted post-test scores than the control group across all five measures. The largest advantage was observed for Useful Description and Specific Application of Physics, suggesting that the graphical-verbal scaffolds in the e-GraVT module were especially effective in helping students make sense of choosing the best physics approach of problem contexts and apply appropriate concepts. Differences in mathematical procedures were positive but more modest, which aligns with earlier findings that conceptual and representational gains may emerge more strongly than purely procedural ones.

Figure 8 presents anonymized student responses to illustrate the development of their problem-solving skills through the procedures implemented in the e-GraVT module. The annotated examples demonstrate how students transitioned from fragmented solutions to more structured approaches, specifically in constructing meaningful problem representations and applying physics concepts systematically as guided by the module's framework.

Figure 7

Comparison of adjusted post means by indicator

Table 7

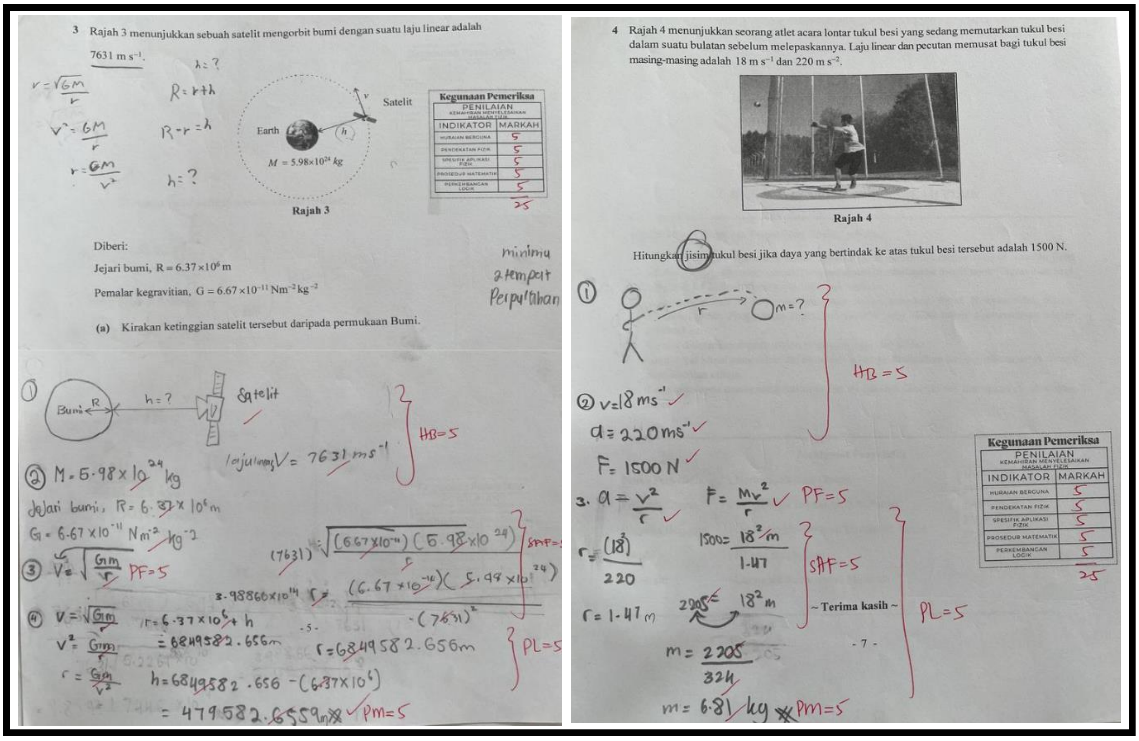
Summary of ANCOVA result for MAPS indicators

Indicators	Treatment (Adj. M ± SE)	Control (Adj. M ± SE)	F(1,96)	*p*	Partial η^2
Useful Description	2.78 ± 0.16	0.38 ± 0.19	90.119	<.001	0.484
Physics Approach	4.08 ± 0.10	3.36 ± 0.12	20.180	<.001	0.174
Specific Application of Physics	3.89 ± 0.13	2.80 ± 0.15	29.270	<.001	0.234
Mathematical Procedures	2.96 ± 0.16	2.34 ± 0.19	6.261	.014	0.061
Logical Progression	3.07 ± 0.16	2.38 ± 0.19	6.906	.010	0.067

Note. Adjusted means (Adj. M) are estimated marginal means calculated at the mean of the pre-test covariate for each respective indicator.

Figure 8

Examples of student responses demonstrating structured problem-solving procedures in gravitation



DISCUSSION

The purpose of this study was to investigate the extent to which the e-GraVT module could enhance students' metacognitive and physics problem-solving skills compared to conventional instruction. Overall, the findings suggest that students in the treatment group tended to show higher metacognitive scores and improved problem-solving performance compared with the control group. These results are consistent with prior work showing that explicit support for metacognition and structured problem-solving procedures can positively influence students' conceptual understanding and performance in Physics (Balta & Awedh, 2017; Dessie et al., 2024).

The effectiveness of the e-GraVT module is evident in the post-test levels of the metacognitive components. After the intervention, the treatment group attained high scores in Knowledge about Cognition, Planning, Evaluation, Debugging, and Information Management, while Monitoring reached a moderate level. These results are consistent with the possibility that the e-GraVT module supported greater awareness of thinking and improvements in planning their work, organizing relevant information, critically evaluating their solutions, and correcting their mistakes.

This pattern echoes findings that metacognitive regulation, particularly planning, monitoring, and evaluation, can supports deeper conceptual understanding and more effective problem-solving strategies in Physics (Hernandez & Ortega, 2023; Schraw & Dennison, 1994; Taasoobshirazi et al., 2015). In other words, they gained greater control over their own learning processes while working on physics tasks, reducing the tendency to overestimate understanding or persist with ineffective approaches (Morphew, 2021).

The comparison between the control and treatment groups further clarifies this pattern. Before the intervention, both groups were generally at a moderate level of cognitive knowledge and regulation, with the treatment group even starting with a lower level of cognitive knowledge. After using the e-GraVT module, however, the treatment group moved to a high level in both cognitive knowledge and cognitive regulation, whereas the control group remained at a moderate level.

This suggests the module may have contributed to a shift from more routine engagement towards more reflective approaches. Similar to previous studies on metacognitive instruction in science, students with higher metacognitive knowledge and regulation are more likely to set clear learning goals, monitor their understanding while solving problems, and select appropriate strategies to improve the quality of their learning (Avargil et al., 2018; Zohar & Barzilai, 2013). The findings regarding physics problem-solving skills also support this interpretation. The treatment group's overall problem-solving score increased from 20.43% to 65.26%, while the control group improved only from 30.85% to 47.95%. Indicator-level analysis suggests the treatment group tended to achieve better outcomes across all five areas, namely, Useful Description, Physics Approach, Specific Application, Mathematical Procedures, and Logical Progression. The largest gains were observed in Useful Description and Specific Application of Physics, which suggests that the graphical and verbal scaffolds embedded in the e-GraVT module helped students better interpret problem contexts and apply suitable physics concepts.

This is in line with research on the CUP model and structured problem-solving frameworks, which have shown that making conceptual reasoning explicit and guiding students through step-by-step procedures can strengthen both qualitative description and the application of principles (Carpendale & Cooper, 2021; Nurlina et al., 2020). The improvement in Mathematical Procedures was positive but more moderate, indicating that conceptual and representational gains were stronger than purely procedural ones, a pattern also reported in studies where metacognitive and representational supports primarily enhance higher-order thinking rather than routine calculation (Mazana et al., 2018).

The relationships among the metacognitive components themselves also have important implications. The high post-test levels in Planning, Evaluation, Debugging, and Information Management point towards the possibility that students who took more responsibility for regulating their own learning tended to show greater improvement, especially in constructing sound physics solutions. These finding parallels prior evidence that self-regulation through planning, strategic information management, and evaluative checking is positively associated with academic achievement and problem-solving success in STEM domains (Balta & Asikainen, 2019). Although Monitoring remained at a moderate level, this may indicate that continuous self-checking during problem-solving is a more demanding skill that requires longer exposure and more explicit practice, as suggested by studies reporting that some metacognitive components are slower to develop than others (Avargil et al., 2018; Daher & Hashash, 2022).

Taken together, the results show that the e-GraVT module functions as more than just a digital resource for delivering physics content. It provides a structured environment in which students must think about how they are learning, not only what they are learning, aligning with research on technology-enhanced, metacognitively rich learning environments in Physics. When students are repeatedly asked to describe situations, choose principles, justify steps, and review their answers, they gradually develop a more questioning and reflective attitude towards knowledge, which is a central characteristic of expert-like physics problem solvers (Nurlina et al., 2020).

These findings contribute to the evidence that metacognitive scaffolds within digital modules can support the development of higher-order thinking and more expert-like problem-solving, though further replication is needed. By simultaneously strengthening metacognitive regulation and domain-specific problem-solving in Physics, the e-GraVT module supports the development of core STEM competencies such as critical thinking, strategic problem-solving, and self-directed learning.

CONCLUSION AND RECOMMENDATIONS

The findings of this study offer encouraging evidence that the e-GraVT module has the potential to support the development of metacognitive and physics problem-solving skills among secondary school students. The data generally align with the primary hypothesis, suggesting that students who engaged with the module showed more noticeable gains in these areas compared to those in the conventional instruction group. In particular, the intervention seemed to be helpful in strengthening the conceptual and representational aspects of problem-solving, as reflected in the students' ability to describe problems and apply physics concepts more systematically.

These results point toward the possibility that when students are provided with metacognitive tools, they may become more reflective and strategic in their learning approach. This, in turn, could help them become more comfortable in interpreting complex problem situations and constructing coherent solutions. While certain areas like monitoring and procedural fluency showed only modest progress, the overall experience suggests that embedding systematic support within a digital environment can be a meaningful way to encourage higher-order thinking.

Moving forward, it is suggested that the e-GraVT module be considered as a complementary part of the physics curriculum. For this to be effective, providing teachers with the necessary technological support and professional development would be beneficial, especially in helping them model metacognitive thinking for their students. Furthermore, future efforts could focus on strengthening self-monitoring skills through simple routines like reflection checklists. Ultimately, shifting the focus of assessments to value the reasoning process, rather than just the final answer, may further nurture a more thoughtful and inquiry-based learning culture in STEM classrooms.

Despite these significant findings, several limitations must be acknowledged. First, the research employed a quasi-experimental design using intact classes rather than random assignment. While this maintained ecological validity, it resulted in baseline imbalances. Although ANCOVA was used to control for these differences, the lack of randomization means unobserved variables, such as classroom climate, could have influenced the results. Second, the intervention was conducted over a relatively short duration of four weeks. While significant gains were observed, this timeframe may be insufficient to capture the long-term internalization of metacognitive habits. Future longitudinal research is needed to determine if these improvements persist over time.

Third, the assessment of metacognition relied on self-reported items. Self-reporting is subject to social desirability bias or inaccurate self-perceptions, which may not fully reflect actual cognitive behaviour. To address this, future studies should incorporate objective qualitative methods, such as think-aloud protocols or interviews, to gain deeper insights into students' real-time metacognitive processes. Finally, as the study was limited to a specific geographical and demographic context, the generalizability of the findings is restricted. Future research should aim to replicate this study using a randomized controlled trial (RCT) or involve a larger, more diverse sample across multiple schools to enhance external validity. These steps would provide a more comprehensive understanding of the e-GraVT module's effectiveness in diverse educational settings.

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Ethical statement

This study received ethical approval from the Ministry of Education Malaysia (Approval Code: KPM.600-3/2/3-eras(22995)). Before data collection, permission was obtained from school authorities and informed consent was secured from all student participants and their parents/guardians. Participation was voluntary and confidential, with all data used exclusively for research purposes.

Competing interests

No conflicts of interest, whether financial, personal, or professional, related to this manuscript.

Author contributions

NO was responsible for the research concept and design, data collection and assembly, data analysis, interpretation, and writing the original draft. SNDM and NMA contributed to the research concept and design and provided critical revision of the manuscript. All authors read, revised, and approved the final version of the article.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI disclosure

During the preparation of this work, the authors used ChatGPT to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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