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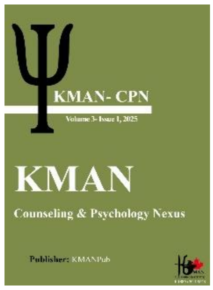

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The Impact of AI-Enabled Prompt Engineering Intervention on Sixth-Grade Students' Academic Achievement, Motivation, and Engagement

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A B S T R A C T

The present study aimed to investigate the effectiveness of an AI-enabled prompt engineering intervention on sixth-grade students' academic achievement, academic motivation, and multidimensional engagement in science learning. This study employed a quasi-experimental pretest–posttest design with a non-equivalent control group. The sample consisted of 30 sixth-grade female students who were assigned to an experimental group ($n = 15$) and a control group ($n = 15$). The experimental group participated in an eight-session AI-supported science learning program in which prompt engineering techniques were used to position the AI system as a Socratic and facilitative tutor rather than a direct provider of answers. Data collection instruments included the Academic Motivation Scale (AMS), a multidimensional engagement questionnaire based on Reeve's model, and a researcher-developed science achievement test. The intervention was implemented over four weeks with two 45-minute sessions per week. Data were analyzed using descriptive statistics and Analysis of Covariance (ANCOVA) in SPSS at a significance level of 0.05. The ANCOVA findings demonstrated a statistically significant effect of the AI-based intervention on all dependent variables ($p < .001$). The intervention explained 67% of the variance in academic achievement (Partial $\eta^2 = .67$), 61% of the variance in academic motivation (Partial $\eta^2 = .61$), and 64% of the variance in total academic engagement (Partial $\eta^2 = .64$). The experimental group showed significantly higher posttest scores compared with the control group across all dimensions of engagement. The strongest effect was observed in agentic engagement, where students demonstrated greater proactive participation, questioning behavior, and instructional agency. Significant improvements were also observed in affective, cognitive, and behavioral engagement dimensions, indicating that AI-assisted instruction enhanced students' emotional involvement, strategic thinking, and persistence in learning activities. The findings provide strong empirical evidence that AI-enabled prompt engineering interventions can substantially improve academic achievement, motivation, and engagement among primary school students.

Keywords: *Artificial Intelligence in Education, Prompt Engineering, Academic Motivation, Agentic Engagement, Academic Achievement, Primary Education.*

1. Introduction

Artificial intelligence (AI) has rapidly emerged as one of the most influential technological developments in contemporary education, fundamentally reshaping teaching practices, learning environments, and student interaction with educational content. Advances in machine learning, natural language processing, adaptive learning systems, and intelligent tutoring technologies have enabled AI to become increasingly integrated into primary, secondary, and higher education contexts (Yim & Su, 2025; Zafari et al., 2022). Educational researchers have argued that AI systems possess the capacity to personalize instruction, provide immediate feedback, identify learning difficulties, and adapt educational materials according to students' individual needs and learning trajectories (Pardamean et al., 2022; Sajja et al., 2024). Within K–12 educational settings, AI applications have expanded considerably through the implementation of intelligent tutoring systems, educational chatbots, virtual assistants, automated assessment systems, and adaptive learning platforms capable of enhancing student participation and facilitating individualized instruction (Aravantinos et al., 2024; Yim & Su, 2025).

The growing use of AI technologies in schools reflects broader educational transformations toward learner-centered instruction and digital learning ecosystems. Traditional teacher-centered instructional models frequently struggle to accommodate the diverse cognitive, motivational, and emotional needs of students within large classrooms. AI-assisted learning systems offer opportunities to address these limitations by delivering differentiated support and creating interactive learning environments that encourage active participation and individualized pacing (Sajja et al., 2024; Zafari et al., 2022). In primary education in particular, AI technologies may be especially valuable because younger learners often require immediate feedback, structured guidance, and engaging learning experiences to sustain motivation and participation (Aravantinos et al., 2024; Jeon, 2024). Consequently, educators and policymakers have increasingly recognized AI not merely as a technological innovation but as a potentially transformative pedagogical tool capable of enhancing educational effectiveness and student development.

One of the most frequently emphasized advantages of AI in education is its ability to foster academic motivation and engagement through adaptive and interactive learning experiences. Motivation represents a central determinant of academic success because it influences the initiation, direction, persistence, and intensity of students' learning behaviors. Engagement, similarly, reflects the extent to which students actively invest emotional, cognitive, behavioral, and agentic energy in learning activities (Fredricks et al., 2019; Reeve et al., 2020). Research consistently demonstrates that students with higher levels of motivation and engagement are more likely to achieve academic success, demonstrate persistence during challenging tasks, and develop positive attitudes toward learning. AI-based educational systems may support these outcomes by creating responsive learning environments that adapt instructional content according to learners' needs while simultaneously encouraging autonomy and active participation (Guo et al., 2024; Yuan & Liu, 2025).

The relationship between AI-assisted learning and student motivation can be understood effectively through the lens of Self-Determination Theory (SDT). According to SDT, human motivation is shaped by the fulfillment of three basic psychological needs: autonomy, competence, and relatedness (Ryan & Deci, 2017; Ryan et al., 2023). Educational environments that support these needs promote more intrinsic forms of motivation, greater persistence, and enhanced psychological well-being. AI-supported learning environments may satisfy students' need for autonomy by allowing greater control over learning pace, task selection, and instructional pathways. Simultaneously, AI systems may strengthen competence through personalized feedback and adaptive scaffolding that help students experience success and mastery. Relatedness may also be enhanced through conversational AI interfaces that provide responsive interaction and emotional support during learning activities (Chiu et al., 2024; Guo et al., 2024). Accordingly, AI-based instructional designs aligned with SDT principles may significantly enhance both the quality and sustainability of students' learning motivation.

Empirical evidence increasingly supports the role of AI in promoting motivational outcomes across educational settings. A bibliometric and systematic review conducted by Al Nabhani et al. indicated that AI-driven educational tools positively influence learning motivation by increasing students' enjoyment, curiosity, and self-regulated learning behaviors (Al Nabhani et al., 2024). Similarly, Alasgarova and Rzayev reported that AI-supported learning environments improved students' academic interest and motivational orientations by increasing interactivity and personalization within the classroom (Alasgarova & Rzayev, 2024). Chiu et al. further demonstrated that AI-based chatbots can significantly increase student motivation when

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teacher support and effective instructional guidance are integrated into the learning environment (Chiu et al., 2024). These findings suggest that AI technologies may provide educational experiences that are more adaptive, interactive, and emotionally engaging than traditional instructional approaches.

Beyond motivation, student engagement has become another critical construct in the study of AI-assisted learning environments. Contemporary models conceptualize engagement as a multidimensional phenomenon encompassing behavioral, cognitive, emotional, and agentic dimensions (Fredricks et al., 2019; Reeve et al., 2020). Behavioral engagement refers to students' participation, effort, and persistence in academic activities, whereas cognitive engagement involves strategic thinking, mental investment, and self-regulation during learning. Emotional or affective engagement reflects students' enjoyment, interest, and emotional connection to learning experiences. Agentic engagement, a more recently emphasized dimension, refers to students' proactive contribution to the instructional process through questioning, expressing preferences, and influencing the direction of classroom learning (Reeve et al., 2020; Reeve et al., 2022). AI-enhanced learning environments may uniquely support agentic engagement because conversational AI systems require students to actively formulate questions, interact dynamically with instructional content, and take initiative during learning interactions.

Recent studies have highlighted the capacity of AI systems to strengthen multiple dimensions of engagement. Yuan and Liu found that AI-supported educational tools significantly increased learners' enjoyment, engagement, and motivation by facilitating interactive and adaptive learning experiences (Yuan & Liu, 2025). Similarly, Song et al. reported that AI-based mobile learning environments enhanced elementary students' engagement and participation through immersive and gamified instructional interactions (Song et al., 2023). Research conducted by Jeon further demonstrated that AI chatbot interactions encouraged active participation and exploratory learning behaviors among young learners by promoting conversational inquiry and personalized communication (Jeon, 2024). These findings are particularly important in primary education because younger students often require engaging and interactive learning contexts to sustain attention and participation.

The emergence of generative AI technologies and prompt engineering strategies has introduced new possibilities for enhancing educational interaction and student agency. Prompt engineering refers to the deliberate design of instructional prompts and AI commands that guide the behavior and responses of AI systems. Within educational settings, prompt engineering can be used to transform AI from a direct answer provider into a facilitative tutor that encourages inquiry, reflection, and analytical thinking. Instead of simply delivering information, AI systems can be strategically instructed to ask guiding questions, scaffold student reasoning, provide hints, and stimulate metacognitive engagement. This instructional approach aligns closely with constructivist and SDT-based perspectives emphasizing active participation and learner autonomy (Artemova, 2024; Guo et al., 2024). Through carefully designed prompts, AI may foster deeper cognitive processing while simultaneously encouraging students to take greater ownership of their learning experiences.

Despite these promising developments, the integration of AI into educational settings is not without challenges and concerns. Researchers have warned that excessive reliance on AI technologies may reduce independent thinking, weaken problem-solving skills, and encourage passive consumption of information if instructional design is poorly implemented (Fuchs, 2023; Suyu et al., 2024). AI systems that provide immediate answers without encouraging reflective thinking may inadvertently undermine cognitive engagement and intrinsic motivation. Furthermore, younger students may be particularly vulnerable to overdependence on AI-generated guidance because of their still-developing self-regulation and critical thinking capacities. Fuchs argued that educational institutions must carefully balance the opportunities and risks associated with generative AI by designing learning environments that prioritize inquiry, reflection, and meaningful interaction rather than automation alone (Fuchs, 2023). Similarly, Suyu et al. emphasized that technological interventions must be pedagogically grounded to ensure that digital learning tools support rather than replace active cognitive effort (Suyu et al., 2024).

Another important limitation within the current literature concerns the relative scarcity of empirical studies focusing specifically on elementary and primary school students. Much existing research on AI in education has concentrated on higher education or secondary school contexts, leaving younger learners comparatively underrepresented (Aravantinos et al., 2024; Yim & Su, 2025). Developmental differences are particularly important because primary school students may interact with AI systems differently

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from older learners in terms of motivation, emotional regulation, communication patterns, and learning strategies. Younger students are often more responsive to interactive feedback, conversational support, and emotionally engaging learning activities. Consequently, AI interventions designed for primary education require age-appropriate instructional structures and motivational strategies capable of supporting foundational cognitive and social-emotional development (Javaid, 2024; Jeon, 2024).

In addition, there remains limited understanding regarding how AI-assisted instructional strategies influence specific dimensions of engagement, particularly agentic engagement. Although previous studies have examined overall engagement and motivation, fewer investigations have explored whether AI can encourage students to become more proactive contributors to the learning process rather than passive recipients of information. Reeve and colleagues emphasized that agentic engagement represents a crucial mechanism through which students shape instructional experiences and optimize learning opportunities (Reeve et al., 2022). Educational environments that promote agentic engagement may lead students to ask more questions, seek clarification, express preferences, and actively influence instructional interactions. Because conversational AI technologies inherently rely on dialogue and interaction, they may be uniquely positioned to cultivate agentic forms of engagement among learners.

Furthermore, while systematic reviews have identified positive relationships between AI and academic outcomes, significant conceptual inconsistencies remain regarding the mechanisms through which AI influences motivation and engagement (Guo et al., 2024; Javaid, 2024). Some studies focus primarily on technological affordances such as adaptive feedback and personalization, whereas others emphasize emotional and social dimensions of AI-supported interaction. Artemova argued that AI-assisted learning should be understood not merely as technological enhancement but as a socially mediated activity system shaped by interaction, communication, and motivational processes (Artemova, 2024). Consequently, there is a growing need for theoretically grounded empirical research examining how AI-based instructional interventions influence both academic and psychological educational outcomes simultaneously.

Given these gaps in the literature, the present study seeks to contribute to the growing body of research on AI-assisted learning by examining the effects of an AI-enabled prompt engineering intervention on sixth-grade students' academic achievement, academic motivation, and multidimensional engagement in science education. Unlike many prior studies that focused primarily on technological effectiveness or higher educational settings, this research investigates how strategically designed AI interactions can support motivation, foster agentic engagement, and enhance academic performance among primary school learners. The intervention was specifically designed to position AI as a facilitative and inquiry-oriented tutor rather than a direct answer provider, thereby encouraging reflective thinking, active participation, and learner autonomy within science instruction. The present study aimed to investigate the effectiveness of an AI-enabled prompt engineering intervention on sixth-grade students' academic achievement, academic motivation, and multidimensional engagement in science learning.

2. Methods and Materials

2.1. *Study Design and Participants*

This study employed a quasi-experimental pretest–posttest design with a non-equivalent control group to investigate the effectiveness of an Artificial Intelligence (AI)-enabled prompt engineering intervention on sixth-grade students' academic achievement, motivation, and engagement in science education. The study was conducted in a primary school setting and involved two intact sixth-grade classrooms selected from the same educational institution. Due to school scheduling and administrative constraints, random assignment at the individual level was not feasible; therefore, one class was assigned to the experimental condition and the other to the control condition. The final sample consisted of 30 female students with a mean age of approximately 11.5 years. Fifteen students participated in the experimental group and fifteen students participated in the control group. Prior to the intervention, baseline equivalence between the two groups was examined using demographic indicators, previous academic performance, and pretest scores on all study variables. No statistically significant differences were observed between the groups at baseline. Ethical approval for the study was obtained from the relevant institutional review board, and written informed consent was secured from parents or legal guardians. In addition, assent was obtained from all student participants before the implementation of the study procedures.

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2.2. Measures

The Academic Motivation Scale (AMS) was used to assess students' motivational orientations toward learning. The instrument was adapted for use with elementary school learners and was grounded in the principles of Self-Determination Theory. The scale consisted of 28 items scored on a five-point Likert continuum ranging from strongly disagree to strongly agree. The instrument measured three major dimensions of motivation, including intrinsic motivation, extrinsic motivation, and amotivation. Intrinsic motivation referred to engagement in learning activities for internal satisfaction and enjoyment, whereas extrinsic motivation reflected participation driven by external rewards or social approval. Amotivation represented the absence of purposeful engagement in academic activities. The scale demonstrated satisfactory psychometric properties in the current study, with a Cronbach's alpha coefficient of 0.88, indicating strong internal consistency among the items.

Student engagement was measured using a multidimensional engagement instrument developed based on Reeve's conceptualization of engagement in educational contexts. The instrument assessed four complementary dimensions of engagement, including affective engagement, behavioral engagement, cognitive engagement, and agentic engagement. Affective engagement referred to students' emotional enjoyment and interest in classroom activities, behavioral engagement assessed persistence and active participation in academic tasks, cognitive engagement measured strategic thinking and mental effort invested in learning, and agentic engagement evaluated students' proactive contribution to the instructional process through questioning, initiative, and active communication. The scale was particularly suitable for the AI-assisted learning environment because of its emphasis on student agency and interaction. Responses were recorded on a five-point Likert scale, and the instrument demonstrated good reliability in the present sample with a Cronbach's alpha coefficient of 0.82.

Academic achievement was evaluated using a researcher-developed science achievement test designed specifically for the instructional content delivered during the intervention. The test focused on science topics related to forces, energy, and earth science, and included both multiple-choice and short-answer analytical questions to assess different cognitive domains. The instrument consisted of 15 items, including 10 multiple-choice questions assessing knowledge and comprehension and 5 short-answer questions assessing application and analytical reasoning. To establish content validity, the test was reviewed by a panel consisting of educational technology specialists and experienced science teachers who evaluated the alignment between the test content, curriculum objectives, and AI-assisted instructional activities. Preliminary pilot testing was conducted with a group of students outside the main sample, resulting in a Cronbach's alpha coefficient of 0.84 and a split-half reliability coefficient of 0.81, indicating acceptable reliability and consistency for measuring academic performance in this context.

2.3. Interventions

The experimental group participated in an AI-enabled science learning program implemented over a four-week period consisting of eight instructional sessions, with two 45-minute sessions conducted each week in the school computer laboratory. Each student interacted individually with an AI-assisted learning interface specifically designed through prompt engineering strategies intended to position the AI system as a facilitative and inquiry-oriented tutor rather than a direct answer provider. The intervention emphasized Socratic dialogue, guided questioning, reflective thinking, and active student participation. Different instructional prompts were systematically designed to promote autonomy, competence, cognitive engagement, and relatedness in accordance with the principles of Self-Determination Theory. During the early sessions, students were encouraged to explore scientific concepts through analytical questioning and guided inquiry. In subsequent sessions, the AI system used narrative-based explanations, hypothetical "what if" scenarios, real-life applications, and reciprocal teaching strategies to deepen understanding and maintain motivation. The researcher served primarily as a technical facilitator and classroom supervisor, while the instructional process was largely mediated through student–AI interaction. In contrast, the control group received traditional science instruction based on conventional classroom teaching methods without AI support. Following completion of the intervention, both groups completed the posttest assessments using the same instruments administered during the pretest phase.

2.4. Data analysis

Data analysis was conducted using the Statistical Package for the Social Sciences (SPSS). Prior to inferential analyses, all data were screened for missing values, outliers, and

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assumptions of normality and homogeneity of variance. Descriptive statistics, including means and standard deviations, were calculated for all study variables across pretest and posttest stages. To examine the effectiveness of the intervention while controlling for baseline differences, Analysis of Covariance (ANCOVA) was performed for each dependent variable using pretest scores as covariates and posttest scores as outcome measures. Separate ANCOVA models were conducted for academic achievement, academic motivation, total engagement, and the individual dimensions of engagement. Effect sizes were interpreted using partial eta squared coefficients to estimate the magnitude of the intervention effects. Statistical significance was evaluated using a two-tailed alpha level of 0.05.

3. Findings and Results

The findings of the present study are presented in two sections, including descriptive findings and inferential findings. Prior to conducting the main statistical analyses, demographic characteristics and baseline equivalence between the experimental and control groups were examined to ensure comparability of participants before implementation of the intervention. The sample consisted of 30 sixth-grade female students equally distributed across the experimental and control groups, with 15 participants in each group. The mean age of students in the experimental group was 11.45 years (SD = 0.52), while the mean age in the control group was 11.58 years (SD = 0.49). Independent samples t-test results indicated no statistically significant difference between the groups regarding age, $t(28) = -0.65$, $p = .510$. In addition, the average previous grade point average (GPA) for the experimental group was 18.40 (SD = 1.15), whereas the control group demonstrated a mean GPA of 18.15 (SD = 1.30), with no statistically significant difference observed between the groups, $t(28) = 0.54$, $p = .590$. All participants had access to the internet and digital learning facilities required for participation in the AI-supported sessions. These findings confirm the homogeneity and baseline equivalence of the two groups prior to the intervention.

Table 1

Descriptive Statistics of Pretest and Posttest Scores for Academic Achievement, Motivation, and Engagement Dimensions

Variable / Dimension	Group	Pretest Mean ± SD	Posttest Mean ± SD
Academic Achievement	Experimental	12.35 ± 2.05	17.80 ± 1.25
	Control	12.15 ± 2.20	13.10 ± 1.90
Academic Motivation	Experimental	3.20 ± 0.65	4.75 ± 0.25
	Control	3.15 ± 0.70	3.35 ± 0.55
Academic Engagement (Total)	Experimental	2.85 ± 0.45	4.65 ± 0.35
	Control	2.90 ± 0.50	3.10 ± 0.60
Affective Engagement	Experimental	3.10 ± 0.55	4.90 ± 0.10
	Control	3.15 ± 0.60	3.25 ± 0.58
Agentic Engagement	Experimental	2.40 ± 0.70	4.55 ± 0.30
	Control	2.45 ± 0.75	2.60 ± 0.65
Cognitive Engagement	Experimental	2.95 ± 0.40	4.40 ± 0.45
	Control	2.90 ± 0.45	3.15 ± 0.50
Behavioral Engagement	Experimental	2.95 ± 0.50	4.75 ± 0.25
	Control	3.10 ± 0.55	3.40 ± 0.60

The descriptive statistics presented in Table 1 demonstrate substantial improvements across all dependent variables among students in the experimental group following participation in the AI-enabled prompt engineering intervention. At the pretest stage, both groups exhibited highly similar scores across academic achievement, academic motivation, total engagement, and all engagement dimensions, indicating strong baseline equivalence prior to intervention implementation. However, following the intervention, the experimental group demonstrated a marked increase in all measured constructs compared with the control group. Academic achievement scores in the experimental group increased from a mean of 12.35 to 17.80, whereas the control group showed only a slight increase from 12.15 to 13.10. Similarly, academic motivation increased substantially in the experimental group from 3.20 to 4.75, while the control group demonstrated only a marginal increase. Total academic engagement also showed a considerable rise in the experimental group, increasing from 2.85 to 4.65, compared with a relatively limited increase in the control group. Among the engagement dimensions, the most pronounced improvement

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was observed in agentic engagement, which increased dramatically from 2.40 to 4.55 in the experimental group, suggesting a significant enhancement in proactive classroom participation, questioning behavior, and learner agency during AI-assisted instruction. Affective, cognitive, and behavioral engagement dimensions also demonstrated notable growth, indicating that the intervention positively influenced emotional involvement, strategic thinking, and sustained participation in learning activities. Overall, the descriptive findings provide preliminary evidence supporting the effectiveness of the AI-supported instructional approach in improving both academic and psychological educational outcomes among primary school students.

Table 2

Results of Analysis of Covariance (ANCOVA) for Academic Achievement, Academic Motivation, and Dimensions of Academic Engagement

Dependent Variable	Source	SS	df	MS	F	p	Partial η²
Academic Achievement	Group	152.40	1	152.40	54.80	0.001	0.67
Academic Motivation	Group	18.45	1	18.45	41.30	0.001	0.61
Academic Engagement (Total)	Group	22.10	1	22.10	48.15	0.001	0.64
Affective Engagement	Group	14.65	1	14.65	39.20	0.001	0.59
Agentic Engagement	Group	19.30	1	19.30	57.45	0.001	0.69
Cognitive Engagement	Group	13.25	1	13.25	33.10	0.001	0.55
Behavioral Engagement	Group	11.85	1	11.85	29.60	0.001	0.52

To evaluate the effectiveness of the AI-enabled intervention while controlling for baseline differences, one-way Analysis of Covariance (ANCOVA) was conducted for academic achievement, academic motivation, total academic engagement, and all dimensions of engagement using pretest scores as covariates. The findings presented in Table 2 indicate that the intervention had a statistically significant effect across all dependent variables at the posttest stage. For academic achievement, the ANCOVA results revealed a highly significant group effect, $F(1, 27) = 54.80$, $p = .001$, with a large effect size (Partial $\eta^2 = .67$). This finding indicates that approximately 67% of the variance in posttest academic achievement scores can be attributed to the AI-supported instructional intervention. Similarly, academic motivation demonstrated a statistically significant intervention effect, $F(1, 27) = 41.30$, $p = .001$, with a substantial effect size (Partial $\eta^2 = .61$), indicating that the AI-based learning environment significantly enhanced students' motivational orientations toward learning. Total academic engagement also yielded a significant intervention effect, $F(1, 27) = 48.15$, $p = .001$, with a large effect size (Partial $\eta^2 = .64$), reflecting considerable improvement in students' engagement levels following participation in the AI-mediated instructional sessions.

At the dimensional level, affective engagement showed a statistically significant increase in the experimental group compared with the control group, $F(1, 27) = 39.20$, $p = .001$, with a large effect size (Partial $\eta^2 = .59$). Agentic engagement demonstrated the strongest intervention effect among all engagement dimensions, $F(1, 27) = 57.45$, $p = .001$, with a very large effect size (Partial $\eta^2 = .69$), indicating that the intervention substantially increased students' proactive participation, questioning behavior, and instructional agency. Cognitive engagement also improved significantly following the intervention, $F(1, 27) = 33.10$, $p = .001$, with an effect size of .55, suggesting enhanced strategic thinking, reflective learning, and mental investment in science activities. In addition, behavioral engagement demonstrated a statistically significant increase, $F(1, 27) = 29.60$, $p = .001$, with a large effect size (Partial $\eta^2 = .52$), reflecting greater persistence, effort, and active classroom participation among students in the experimental group. Overall, the ANCOVA findings confirm that the AI-enabled prompt engineering intervention exerted broad and substantial effects on both educational achievement and multidimensional engagement outcomes among sixth-grade learners.

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Table 3

Comparison of Posttest Means Across Academic Variables and Dimensions of Engagement

Variable / Dimension	Experimental Group Mean	Control Group Mean	p-value
Academic Achievement	17.80	13.10	0.001
Academic Motivation	4.75	3.35	0.001
Academic Engagement (Total)	4.65	3.10	0.001
Affective Engagement	4.90	3.45	0.001
Agentic Engagement	4.55	2.80	0.001
Cognitive Engagement	4.40	3.25	0.010
Behavioral Engagement	4.65	3.60	0.050

A more detailed comparison of posttest means was conducted to examine differences between the experimental and control groups across academic achievement, motivation, and the multidimensional components of engagement. As shown in Table 3, students who participated in the AI-enabled intervention achieved substantially higher posttest scores across all variables compared with students in the traditional instructional condition. Academic achievement scores in the experimental group reached a mean of 17.80 compared with 13.10 in the control group, with the difference reaching statistical significance ($p = .001$). Likewise, academic motivation scores were significantly higher among students exposed to AI-assisted learning, with the experimental group obtaining a mean score of 4.75 compared with 3.35 in the control group. Total academic engagement also differed significantly between groups, with students in the intervention condition demonstrating markedly higher engagement levels overall.

Among the engagement dimensions, affective engagement demonstrated one of the largest differences between groups, with the experimental group reporting substantially greater emotional enjoyment and positive classroom experiences compared with the control group. The most pronounced difference emerged in agentic engagement, where students in the AI-supported condition displayed significantly greater levels of initiative, active contribution, and questioning behavior during learning activities. Cognitive engagement scores were also significantly higher in the experimental group, suggesting that the intervention enhanced concentration, strategic processing, and deeper mental involvement in science learning tasks. In addition, behavioral engagement scores demonstrated a statistically meaningful difference favoring the experimental group, indicating stronger persistence, participation, and task-oriented behaviors during classroom instruction. Collectively, these findings indicate that the AI-enabled prompt engineering intervention positively influenced not only students' academic outcomes but also the quality and depth of their engagement with the learning process across emotional, behavioral, cognitive, and agentic dimensions.

4. Discussion

The primary objective of the present study was to investigate the effectiveness of an AI-enabled prompt engineering intervention on sixth-grade students' academic achievement, academic motivation, and multidimensional engagement in science learning. The findings demonstrated that the intervention produced statistically significant improvements across all dependent variables, including academic achievement, academic motivation, total academic engagement, and all dimensions of engagement. Overall, students who participated in the AI-supported instructional program achieved substantially higher posttest scores compared with students who received traditional instruction. These findings provide strong evidence that strategically designed AI-mediated educational environments can positively influence both cognitive and psychological dimensions of learning among primary school students.

One of the most important findings of the present study was the substantial improvement observed in academic achievement among students in the experimental group. The ANCOVA findings indicated that the AI-enabled intervention explained a large proportion of the variance in posttest science achievement scores. This result suggests that AI-assisted instruction can significantly improve learning outcomes when instructional interactions are carefully structured through prompt engineering strategies. The findings are highly consistent with previous studies demonstrating the educational effectiveness of AI-supported learning systems in improving academic performance and conceptual understanding (Sajja et al., 2024; Yim & Su, 2025). AI systems are capable of providing immediate feedback, individualized scaffolding, adaptive pacing, and personalized learning pathways, all of which may contribute to enhanced comprehension and retention of instructional content (Pardamean et al., 2022; Zafari et al., 2022). In the present study, students were able to interact dynamically with AI-based instructional prompts that encouraged reflective inquiry and guided problem-solving rather than passive memorization. This instructional structure likely facilitated deeper cognitive processing and promoted more meaningful engagement with science concepts.

The findings regarding academic achievement also align closely with the broader literature emphasizing the pedagogical value of AI-assisted personalization. Sajja et al. argued that AI-enabled intelligent assistants improve educational outcomes by continuously adapting instructional content to learners' performance and cognitive needs (Sajja et al., 2024). Similarly, Zafari et al. highlighted that AI applications in K–12 education enhance learning efficiency by identifying individual strengths and weaknesses and adjusting instructional experiences accordingly (Zafari et al., 2022). In the current study, the AI system functioned not as a direct answer generator but as an interactive facilitator encouraging analytical thinking and guided exploration. Such an approach likely prevented overreliance on automated responses while simultaneously supporting students' understanding and mastery of scientific concepts. The intervention therefore appears to have successfully balanced instructional support with cognitive challenge, thereby enhancing academic achievement outcomes.

Another major finding of the present study was the significant increase in academic motivation among students in the experimental group. The AI-enabled intervention produced a strong positive effect on students' motivational orientations toward learning, supporting the proposition that AI-assisted instructional environments can foster more self-determined forms of motivation. This finding is consistent with previous research demonstrating that AI-based educational systems can increase students' interest, enjoyment, and willingness to participate in learning activities (Al Nabhani et al., 2024; Alasgarova & Rzayev, 2024). The present findings may be interpreted effectively through the theoretical framework of Self-Determination Theory, which emphasizes the importance of autonomy, competence, and relatedness in promoting intrinsic motivation (Ryan & Deci, 2017; Ryan et al., 2023).

The AI-supported intervention implemented in the current study appears to have supported all three psychological needs identified by Self-Determination Theory. First, students experienced greater autonomy because they were encouraged to actively interact with the AI system, formulate questions, and influence the direction of instructional dialogue. Rather than receiving passive teacher-centered instruction, learners engaged in exploratory and self-directed interactions that increased their sense of control over the learning process. Second, the AI system enhanced students' feelings of competence by providing immediate and adaptive feedback that scaffolded understanding while reinforcing successful performance. Third, the conversational and responsive nature of the AI environment may have fostered a sense of relatedness by creating a supportive and interactive learning atmosphere. Previous studies have similarly shown that AI-based chatbots and adaptive systems can improve motivation by increasing interactivity and emotional responsiveness during learning (Chiu et al., 2024; Guo et al., 2024). Consequently, the motivational improvements observed in the present study may reflect the successful alignment between AI instructional design and fundamental psychological needs.

The significant improvement observed in total academic engagement further highlights the educational potential of AI-enabled learning environments. Engagement is widely recognized as a multidimensional construct encompassing emotional, behavioral, cognitive, and agentic dimensions of participation in academic activities (Fredricks et al., 2019; Reeve et al., 2020). The findings demonstrated that the AI-supported intervention enhanced engagement across all of these dimensions, suggesting that AI-mediated instruction can influence not only what students learn but also how they emotionally and behaviorally participate in the learning process. These findings are consistent with previous research indicating that AI-enhanced educational technologies promote active participation, sustained attention, and increased learner involvement (Song et al., 2023; Yuan & Liu, 2025).

The substantial increase observed in affective engagement indicates that the AI-supported instructional environment enhanced students' enjoyment and emotional connection to learning activities. Students in the experimental group demonstrated significantly higher levels of interest and positive emotional involvement compared with the control group. This finding aligns with previous studies reporting that AI-based educational interactions can make learning experiences more stimulating, immersive, and enjoyable for learners (Jeon, 2024; Song et al., 2023). Younger learners are often particularly responsive to interactive and conversational technologies because such systems provide immediate responses and maintain continuous engagement through dynamic interaction. The

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use of prompt engineering strategies in the present study may have further contributed to affective engagement by encouraging curiosity, exploration, and reflective inquiry rather than repetitive or passive instructional interaction.

The findings regarding cognitive engagement are also particularly important. Students in the experimental group demonstrated significantly greater levels of concentration, strategic thinking, and mental investment in learning tasks compared with students receiving traditional instruction. Cognitive engagement is closely associated with deep learning, metacognition, and self-regulated learning processes (Reeve et al., 2020). The AI-supported instructional design implemented in the present study likely enhanced cognitive engagement by requiring students to actively interpret questions, analyze information, and construct responses during interaction with the AI system. Rather than simply receiving information, learners participated in guided inquiry and reflective problem-solving activities that promoted sustained mental effort. Similar findings have been reported in prior research demonstrating that AI-assisted learning environments can improve cognitive engagement by encouraging exploratory learning and strategic processing (Guo et al., 2024; Javaid, 2024).

Behavioral engagement also improved significantly among students exposed to the AI-enabled intervention. Students in the experimental group demonstrated higher levels of persistence, classroom participation, and effort during instructional activities. This finding supports previous research suggesting that AI-enhanced learning environments can increase students' willingness to participate actively and remain engaged with academic tasks over time (Song et al., 2023; Yuan & Liu, 2025). Behavioral engagement may have increased because the AI system provided continuous interaction and personalized support that sustained students' attention and reduced disengagement during learning activities. Furthermore, the novelty and interactivity associated with AI-supported instruction may have contributed to greater enthusiasm and sustained participation among elementary school learners.

Perhaps the most noteworthy finding of the present study was the dramatic increase in agentic engagement among students in the experimental group. Agentic engagement refers to students' proactive contribution to the instructional process through asking questions, expressing preferences, and influencing the direction of learning activities (Reeve et al., 2020; Reeve et al., 2022). The intervention produced the strongest effect size for this dimension, indicating that students exposed to AI-supported instruction became substantially more proactive and participatory during learning. This finding is theoretically and practically significant because agentic engagement is increasingly recognized as a critical mechanism through which learners optimize educational opportunities and shape their instructional experiences.

The conversational structure of AI-assisted learning likely played a central role in enhancing agentic engagement. Unlike traditional teacher-centered instruction in which students often assume passive roles, AI-mediated interactions required learners to formulate prompts, ask questions, and respond actively during instructional dialogue. This interactive process may have encouraged students to perceive themselves as active contributors rather than passive recipients of knowledge. Reeve et al. emphasized that educational environments promoting student initiative and agency lead to stronger learning outcomes and greater psychological investment in learning activities (Reeve et al., 2022). Similarly, Jeon found that conversational AI systems encourage exploratory behavior and active learner participation among younger students (Jeon, 2024). The present findings strongly support these theoretical perspectives and suggest that AI-enabled prompt engineering may represent a particularly effective strategy for cultivating learner agency in primary education settings.

Although the findings of the present study are highly positive, they must also be interpreted in light of ongoing concerns regarding AI integration in educational contexts. Some scholars have warned that excessive dependence on AI technologies may weaken independent thinking and reduce opportunities for authentic cognitive struggle if instructional design is not carefully managed (Fuchs, 2023; Suyu et al., 2024). The current intervention attempted to address these concerns by designing prompts that encouraged inquiry, reflection, and analytical reasoning rather than direct answer retrieval. Nevertheless, the broader educational challenge remains ensuring that AI systems function as facilitators of active learning rather than replacements for human cognition and teacher guidance. The findings of the present study therefore support the perspective that AI can be educationally beneficial when implemented within pedagogically grounded frameworks emphasizing student agency, reflective inquiry, and psychological need satisfaction.

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5. Conclusion

The results contribute to the relatively limited literature focusing specifically on primary school learners. Many previous investigations have concentrated on secondary or higher education settings, despite the possibility that younger learners may respond differently to AI-supported instructional environments (Aravantinos et al., 2024; Yim & Su, 2025). The present findings demonstrate that elementary school students can meaningfully engage with AI-assisted instructional systems when interventions are developmentally appropriate and carefully structured. The observed improvements across motivational and engagement variables suggest that younger learners may particularly benefit from interactive, adaptive, and conversational forms of educational support.

One limitation of the present study concerns the relatively small sample size and the use of participants from a single educational setting, which may limit the generalizability of the findings to broader student populations. Additionally, the intervention was implemented over a relatively short duration, making it difficult to determine whether the observed motivational and engagement improvements would remain stable over longer periods of time. Another limitation involves the exclusive reliance on self-report measures for assessing motivation and engagement, which may be influenced by social desirability or response bias. Furthermore, because the study focused exclusively on female sixth-grade students, caution should be exercised when generalizing the findings to male students or different developmental age groups.

Future research should examine the long-term effects of AI-enabled prompt engineering interventions across diverse educational contexts and grade levels. Longitudinal studies would be particularly valuable for investigating whether improvements in motivation, engagement, and academic achievement can be sustained over time. Future investigations should also explore additional psychological and educational variables, including self-regulated learning, creativity, critical thinking, cognitive load, and digital literacy. Comparative studies examining different forms of AI-assisted instructional design may further clarify which specific AI interaction strategies are most effective for promoting learner agency and deep engagement. In addition, integrating qualitative approaches such as classroom observations and student interviews may provide richer insight into students' experiences and perceptions of AI-mediated learning environments.

Educational practitioners and policymakers should consider integrating AI-assisted instructional systems into primary education in ways that prioritize inquiry-based learning, student autonomy, and active participation. AI technologies should not be viewed as replacements for teachers but rather as complementary instructional tools capable of supporting personalized and interactive learning experiences. Teachers should receive appropriate professional training on effective prompt engineering strategies and pedagogically grounded AI integration practices to ensure that technology enhances rather than diminishes cognitive and social development. Schools should also develop ethical and instructional guidelines governing AI use in classrooms to maintain balanced educational environments that encourage independent thinking, creativity, and collaborative learning alongside technological innovation.

Authors' Contributions

Authors equally contributed to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

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