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The Role of Generative AI in Enhancing Primary School Science Achievement: A Conceptual Paper

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Abstract

Generative artificial intelligence (GenAI) has attracted sustained interest in science education for its capacity to personalise explanations, render submicroscopic processes visible, and maintain learner engagement. This conceptual paper theorises how GenAI can strengthen primary pupils' conceptual understanding in abstract topics (for example, the particulate nature of matter) and specifies the conditions under which it improves science achievement. Drawing on constructivist and sociocultural perspectives (Piaget; Vygotsky) together with the Cognitive Theory of Multimedia Learning (CTML) and Cognitive Load Theory (CLT), the paper advances the AAE framework (Adaptive scaffolding, Active multimodal processing, and Equitable personalisation) as the core set of mechanisms that link GenAI design features to learning outcomes. From this framework, we derive testable propositions: (a) aligning narration with animation and enabling learner controlled segmenting reduces extraneous load and increases germane processing; (b) adaptive sequences of predict, observe, and explain repair common misconceptions; and (c) personalised pacing or modality combined with structured collaborative scripts promotes equitable participation and achievement. A staged research agenda is outlined, including curriculum aligned two tier concept measures. The paper concludes with pedagogical and ethical implications for teachers (orchestration, verification of AI generated content), institutional leadership and policy makers. By consolidating theory, design principles, and propositions, the paper provides a roadmap for rigorous and context sensitive evaluation of GenAI in primary science.

Keywords: Generative Artificial Intelligence, Science Education, STEM

1. Introduction

Science achievement at the primary school level is a key determinant of students' future engagement with STEM fields and overall scientific literacy. International assessments such as Trends in International Mathematics and Science Study **(**TIMSS) and Programme for International Student Assessment (PISA) reveal that many students demonstrate only a superficial understanding of core scientific concepts, with significant gaps in applying knowledge to real-world contexts (Mullis *et al*., 2020; OECD, 2023) [17, 18]. Within Malaysia, national assessment reports indicate that topics requiring abstract reasoning, particularly matter, consistently yield lower achievement scores than other areas in the science curriculum (MOE, 2022) [16]. Matter introduces fundamental concepts such as particle theory, states of matter, and phase transitions. However, these concepts are abstract and often invisible to direct observation, making them challenging for young learners to conceptualize and resulting in persistent misconceptions (Lim & Fong, 2023; Cheng *et al*., 2022) [11, 5].

Studies on misconceptions highlight that children often rely on everyday experiences to explain phenomena, leading to alternative frameworks inconsistent with scientific models (Driver *et al*., 1994) [7]. Common misconceptions include the belief that gas particles lack mass due to their invisibility or that particles in solids are completely immobile (Ahmad & Noor, 2021) [1]. Traditional teacher-centered methods, which emphasize memorization over inquiry, have proven less effective in fostering conceptual change in such abstract topics (Rahman *et al*., 2022) [20]. Gender differences in science achievement add another layer of complexity. While overall performance gaps are narrowing, topic-specific and cognitive domain differences persist across multiple contexts (Chai *et al*., 2021) [4]. In Malaysia and Southeast Asia, girls tend to excel in written assessments requiring factual recall and conceptual explanation, whereas boys often perform better in spatial and procedural problem-solving (Tan & Karim, 2021) [22]. Socialization, teacher expectations, and classroom dynamics influence these patterns and can amplify or minimize disparities (Wong *et al*., 2022) [24].

Generative GenAI offers a promising avenue to address these challenges. With capabilities for adaptive feedback, personalized explanations, and dynamic visualization, GenAI-based modules can simulate particle interactions and phase changes, making abstract concepts tangible (Lau & Lee, 2023; Luckin, 2023) [9, 13]. Additionally, AI-driven adaptive systems can provide gender-neutral support, tailoring instruction to individual learners while minimizing bias (Siemens, 2022) [21].

This study addresses critical gaps in current research by providing quantitative evidence on the impact of GenAI on primary science achievement in abstract topics such as matter while also exploring the potential of AI-assisted instruction to reduce gender disparities in early STEM learning. Utilizing a quasi-experimental design, the study aims to generate empirical insights that can guide curriculum development, inform pedagogical strategies, and support the effective integration of AI technologies in science education.

1.1 Research Objectives

1.To identify the effectiveness of GenAI in increasing Year 5 students' achievement in the topic of Matter.

2.To determine whether there are differences in science achievement between male and female students when exposed to GenAI-assisted learning on the topic of matter.

1.2 Research Questions

1. Is there a significant difference in Year 5 students' science achievement on the topic of Matter between those taught using GenAI and those taught using conventional teaching methods?

2. Are there significant differences in science achievement between male and female students who learn the topic of Matter using GenAI assisted learning?

1.3 Research Hypotheses

H_{01}: There is no significant difference in science achievement on the topic of Matter between Year 5 students who learn using GenAI-assisted instruction and those who receive conventional teaching.

H_{02}: There is no significant difference in science achievement between male and female students when using GenAI assisted learning in the topic of Matter.

2. Literature Review and Theoretical Framework

Generative Artificial Intelligence (GenAI) represents a significant advancement in educational technology due to its ability to create adaptive content, generate personalized feedback, and simulate real-time learning scenarios based on student interactions. Unlike traditional digital learning tools, GenAI leverages large language models and generative algorithms to provide dynamic responses tailored to individual learners' needs (Lau & Lee, 2023; Luckin, 2023) [9, 13]. In science education, these affordances are particularly valuable for topics requiring visualization of abstract or microscopic phenomena, such as matter. Research demonstrates that AI-driven adaptive systems can enhance students' conceptual understanding, motivation, and engagement compared to static, teacher-centered approaches (Cheng *et al*., 2022; Wong *et al*., 2022) [5, 24].

Integrating GenAI aligns closely with constructivist learning theories that emphasize active participation, knowledge construction, and scaffolding. Piaget's cognitive development theory underscores the importance of experiential learning in facilitating conceptual change (Piaget, 1972) [19]. Similarly, Vygotsky's social constructivism highlights the role of guided interaction and scaffolding, which can be replicated through GenAI's adaptive prompts and feedback mechanisms (Vygotsky, 1978) [23]. These theoretical underpinnings support the hypothesis that GenAI can serve as an effective pedagogical tool in primary science education.

The topic of matter is a core component of the primary science curriculum and serves as the foundation for understanding chemistry and physics in later schooling. However, numerous studies report that students experience significant difficulties in grasping particle theory, states of matter, and phase transitions due to the abstract nature of these concepts (Rahman *et al*., 2022; Lim & Fong, 2023) [20, 11]. Students often hold alternative conceptions based on everyday experiences, such as believing that gases have no weight or that particles in solids are completely immobile (Driver *et al*., 1994; Ahmad & Noor, 2021) [7, 1]. These misconceptions are resistant to change without targeted instructional strategies that provide visual, interactive, and inquiry-based learning experiences.

Traditional didactic teaching methods, while effective for knowledge transmission, are less effective for conceptual change in abstract topics (Rahman *et al*., 2022) [20]. Research shows that technology-enhanced learning, particularly simulations and dynamic visualizations, can significantly improve understanding of matter by allowing students to observe invisible processes at the particle level (Cheng *et al*., 2022) [5]. GenAI extends these benefits by generating personalized explanations and enabling students to explore "what-if" scenarios in real time, thus deepening conceptual understanding and promoting higher-order thinking (Lau & Lee, 2023) [9]. Recent classroom studies with Malaysian primary learners echo these trends: Scratch-based tasks improved achievement and motivation in astronomy topics (Ming, Chongo, & Lapawi, 2023) [15], while computer-based simulations and virtual labs yielded gains in Earth–Sun concepts and electricity (Lee & Chongo, 2025; Lim & Chongo, 2025) [10, 12].

Gender disparity in science achievement remains a persistent concern, with evidence suggesting that differences may emerge as early as primary school (Chai *et al*., 2021) [4]. Studies in Southeast Asia, including Malaysia, indicate that female students often outperform males in tasks requiring verbal reasoning and conceptual explanation, while male students may excel in spatial and procedural problem-solving (Tan & Karim, 2021) [22]. These patterns are influenced by sociocultural expectations, teacher-student interactions, and classroom dynamics (Wong *et al*., 2022) [24].

Educational interventions aimed at bridging gender gaps emphasize the importance of equitable, learner-centered environments. AI-driven adaptive learning platforms, such as GenAI, have the potential to provide personalized support that minimizes teacher bias and addresses individual learning needs regardless of gender (Siemens, 2022) [21]. Preliminary studies show that AI-based environments can reduce performance disparities by adapting content delivery to learners' pace, confidence level, and prior knowledge (Luckin, 2023) [13]. Investigating the interaction between GenAI use and gender in the context of primary science achievement is thus a critical step toward ensuring inclusivity in STEM education.

Generative Artificial Intelligence (GenAI) represents a major innovation in educational technology due to its ability to create adaptive content, provide personalized feedback, and simulate real-time learning scenarios based on student interactions (Lau & Lee, 2023; Luckin, 2023) [9, 13]. Unlike traditional digital tools that operate with static content, GenAI leverages large language models and generative algorithms to create dynamic learning experiences tailored to individual cognitive needs. In science education, these affordances are particularly critical for topics requiring visualization of abstract or microscopic phenomena such as matter, which often leads to misconceptions due to its invisible nature (Cheng *et al*., 2022; Rahman *et al*., 2022) [5, 20]. Current research demonstrates that AI-driven adaptive learning systems can enhance students' conceptual understanding, motivation, and engagement compared to traditional teacher-centered methods (Wong *et al*., 2022; Ahmad & Noor, 2021) [24, 1]. Moreover, the use of GenAI aligns with the demands of 21st-century skills such as critical thinking, problem-solving, and self-directed learning (Siemens, 2022; Luckin, 2023) [21, 13].

2.1 Constructivist Foundations

This study is fundamentally grounded in Piaget's Cognitive Development Theory, which emphasizes that meaningful learning arises when learners actively engage with their environment to construct new knowledge structures. According to Piaget (1972) [19], children in the concrete operational stage (typically ages 7–11, aligning with primary school years) develop logical reasoning skills but still rely heavily on tangible experiences to understand abstract concepts. In the context of primary science education, this stage presents challenges for teaching topics such as the particle theory of matter, as these concepts are largely invisible and abstract.

GenAI-based modules bridge this gap by providing immersive, interactive simulations that make abstract particle interactions visible and manipulable. Students can engage with dynamic visualizations of states of matter, observe particle motion during phase transitions, and conduct "what-if" experiments in a safe virtual environment. These experiences foster assimilation, where learners integrate new information into existing mental frameworks, and accommodation, where they adjust their frameworks to resolve cognitive conflict and correct misconceptions (Cheng *et al*., 2022; Rahman *et al*., 2022) [5, 20].

This approach strongly aligns with constructivist pedagogy, which views knowledge as actively built by the learner rather than passively received from the teacher. It also resonates with Bruner's spiral curriculum, where abstract ideas are introduced in progressively complex forms supported by concrete experiences (Bruner, 1960) [3]. GenAI's capacity for adaptive scaffolding allows these experiences to be personalized to individual readiness levels, ensuring that each learner engages at an appropriate cognitive depth.

Furthermore, GenAI-enhanced modules embody the principles of inquiry-based learning, enabling students to ask questions, test hypotheses, and explore multiple representations of scientific phenomena. According to Hmelo-Silver *et al*. (2007) [8], such environments cultivate higher-order thinking and problem-solving skills because they require active exploration, reflection, and knowledge construction. By integrating adaptive AI feedback with experiential simulations, GenAI situates learners within a dynamic constructivist learning cycle, supporting deep conceptual change and transfer of understanding to novel contexts.

2.2 Vygotsky's Social Constructivism

Complementing Piaget's individual cognitive perspective, the study draws on Vygotsky's Social Constructivist Theory, which places social interaction and cultural mediation at the heart of learning. A central concept in this framework is the Zone of Proximal Development (ZPD), defined as the gap between what a learner can achieve independently and what they can accomplish with guidance (Vygotsky, 1978) [23]. GenAI modules function as digital scaffolds, providing adaptive prompts, real-time feedback, and contextual hints that replicate teacher mediation in the ZPD (Siemens, 2022) [21]. Through intelligent algorithms, GenAI adjusts the complexity of tasks and the type of support based on learner responses, ensuring that instructional input remains within the optimal challenge zone. This adaptive scaffolding supports not only content mastery but also the development of metacognitive skills, as students learn to monitor and regulate their own understanding.

Beyond individual scaffolding, GenAI also facilitates collaborative knowledge building, a core tenet of Vygotsky's theory. AI-supported platforms can mediate group problem-solving tasks, provide equitable participation cues, and generate prompts that stimulate peer dialogue. Such features align with the socio-cultural view of learning as a co-constructed process enriched by shared experiences and cultural tools (Luckin, 2023) [13]. In primary science classrooms, these capabilities enable students to engage in socially mediated inquiry, where ideas are negotiated, misconceptions are challenged, and collective understanding is developed through dialogue.

2.3 Cognitive Theory of Multimedia Learning

The integration of GenAI into science instruction is further supported by Mayer's Cognitive Theory of Multimedia Learning (CTML), which posits that learning is optimized when verbal and visual information are processed simultaneously through dual channels (Mayer, 2009) [14]. CTML emphasizes three key principles highly relevant to GenAI design:

1. Multimedia Principle: Students learn better from words and pictures together than from words alone. GenAI modules combine adaptive text/audio explanations with dynamic particle simulations to illustrate scientific phenomena in multiple modalities (Cheng *et al*., 2022) [5].
2. Modality Principle: Using spoken narration with visual animations reduces cognitive overload compared to on-screen text. GenAI can leverage this by providing voice-based guidance synchronized with visual representations of particle interactions.
3. Segmenting and Personalization Principles: Breaking content into learner-controlled segments and presenting it in a conversational style enhances understanding. GenAI's adaptive pacing and personalized prompts operationalize these principles automatically.

For teaching matter, CTML is especially critical because students must construct accurate mental models of invisible

phenomena**.** Traditional static diagrams often fail to convey particle dynamics, leading to persistent misconceptions (Driver *et al*., 1994; Ahmad & Noor, 2021) [7, 1]. Targeted classroom action research has shown these misconceptions can be reduced when instruction explicitly surfaces and repairs naïve models (Chia *et al*., 2023) [6]. GenAI overcomes this by generating real-time animations and simulations that visualize particle behavior across different states of matter, enabling students to build more robust conceptual representations while minimizing extraneous cognitive load.
When integrated with constructivist and socio-cultural theories, CTML provides a comprehensive cognitive framework for understanding how GenAI can enhance primary science learning. Together, these theories underscore the pedagogical potential of GenAI as a tool that unites experiential, social, and cognitive dimensions of learning to address persistent challenges in teaching abstract scientific concepts.

2.4 Gender and Equity Perspectives
From a socio-cultural perspective, gender differences in science achievement at the primary level are often associated with teacher expectations, peer interactions, and cultural norms (Wong *et al*., 2022) [24]. Studies indicate that female students tend to excel in conceptual explanation and verbal reasoning tasks, while male students often perform better in procedural and spatial problem-solving (Chai *et al*., 2021; Tan & Karim, 2021) [4, 22]. AI-driven adaptive systems like GenAI have the potential to minimize these disparities by providing equitable and personalized learning experiences free from unintended gender bias (Siemens, 2022) [21]. Preliminary research suggests that AI-based platforms can adjust support levels, content delivery styles, and pacing according to individual needs, thereby improving equity in STEM achievement (Luckin, 2023) [13].

3. Methodology
3.1 Research Design
Research designs that aim to evaluate the impact of interventions without utilizing random assignment are classified as quasi-experimental studies (Anthony *et al*., 2006) [2]. Guided by this definition, the present research adopted a quasi-experimental approach to examine the effectiveness of a GenAI in enhancing Year 5 students' in learning the topic of matter. The study is grounded in a quantitative research framework, and the quasi-experimental design was selected as it allows for the investigation of causal relationships within authentic classroom settings where randomization is not feasible.

3.2 Sampling
We propose a purposive sampling approach involving two intact Year 5 classes from comparable schools. Class selection will be guided by prior Science attainment, basic demographic profile, timetable compatibility, and device/access readiness. One class will continue business-as-usual instruction (control), and the other will receive a GenAI-enhanced instructional sequence (treatment). Each class is expected to comprise approximately 30–35 students**.** Baseline equivalence will be verified using existing Science test scores; any residual imbalance will be addressed analytically (ANCOVA). This design aims to minimise the influence of pre-existing differences and strengthen causal inferences about the GenAI intervention in authentic classroom settings. All procedures will adhere to ethical guidelines (school and parent/guardian consent, data confidentiality, right to withdraw). In a follow-up phase, we propose stratified sampling across multiple schools to enhance external validity**.**

3.3 Instrument
Data were collected using two instruments, one of which was the Science Achievement Test (SAT). The SAT was specifically developed to evaluate students' conceptual understanding of the topic of matter and consisted of ten objective items. The test was constructed in alignment with the *Curriculum and Assessment Standard Document* (DSKP) and modeled after the *Final Examination of the Academic Session* (UASA) format to ensure curriculum validity. The SAT was administered twice, serving as both a pre-test and a post-test, with a completion time of 30 minutes. Its primary purpose was to measure the cognitive gains achieved by students in each group following the instructional intervention.

3.4 Data Analysis
Quantitative data will be obtained through the administration of pre- and post-test assessments designed to evaluate students' achievement. These instruments aim to measure the extent to which the use of the virtual laboratory in learning the topic of matter influences students' performance. Descriptive statistics will be applied to summarize and present the overall data trends, whereas inferential statistics, including the independent samples t-test, will be utilized to determine whether there are statistically significant differences in achievement between the treatment and control groups.

4. Conclusion
This conceptual paper highlights the potential of Generative Artificial Intelligence (GenAI) as a transformative tool in primary science education, particularly for the topic of matter. By leveraging adaptive feedback, personalized explanations, and dynamic visualizations, GenAI has the capacity to address persistent challenges in teaching abstract scientific concepts and mitigating common misconceptions among young learners. The quasi-experimental design proposed in this study offers a structured approach to generate empirical evidence on the effectiveness of GenAI-assisted learning compared to traditional instruction.
In addition to evaluating overall achievement, this study emphasizes the importance of examining gender differences in learning outcomes, thereby contributing to ongoing discussions on equity in STEM education. Findings from this research are expected to inform curriculum design, pedagogical strategies, and policy decisions related to AI integration in primary education. Ultimately, this work aims to bridge the gap between emerging AI technologies and practical classroom applications, ensuring that advancements in educational innovation translate into meaningful improvements in student learning and engagement.

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