A Human-Centered Learning and Teaching Framework Using Generative Artificial Intelligence for Self-Regulated Learning Development Through Domain Knowledge Learning in K–12 Settings

Siu-Cheung Kong and Yin Yang

***Abstract*—The advent of generative artificial intelligence (AI) has ignited an increase in discussions about generative AI tools in education. In this study, a human-centered learning and teaching framework that uses generative AI tools for self-regulated learning development through domain knowledge learning was proposed to catalyze changes in educational practices. The framework illustrates how generative AI tools can revolutionize educational practices and transform the processes of teaching and learning to become human-centered. It emphasizes the evolving roles of teachers, who increasingly become skillful facilitators and humanistic storytellers who craft differentiated instructions and attempt to develop students' individualized learning. Drawing upon insights from neuroscience, the framework guides students to employ generative AI tools to augment their attentiveness, stimulate active engagement in learning, receive immediate feedback, and encourage self-reflection. The pedagogical approach is also reimagined; teachers equipped with generative AI tools and AI literacy can refine their teaching strategies to better equip students to meet future challenges. The practical application of the framework is demonstrated in a case study involving the development of Chinese language writing ability among primary students within a K–12 educational context. This article also reports the results of a 60-h development programme for teachers. Specifically, providing in-service teachers with cases involving uses of the proposed framework helped them to better understand the generative AI concepts and integrate them into their teaching and learning and increased their perceived ability to design AI-integrated courses that would enhance students' attention, engagement, confidence, and satisfaction.**

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I. Introduction

THE advent of artificial intelligence (AI) has ushered in an era of profound transformation across various sectors, including education. Generative AI is characterized by its capacity to generate content, including texts, audios, pictures, videos, and programming codes [1]. Despite its vast potential, generative AI has not been fully integrated into educational contexts [2], [3], [4], and this lag in integration is especially evident when compared with its rapid adoption in fields, such as healthcare, business operations, and software engineering [5], [6]. This lag is due to the insufficient attention given to the role of teachers in the deployment and orchestration of AI tools [2], [7].

The integration of generative AI tools into educational practices requires a robust framework that supports learning and teaching. Existing frameworks, such as those advocated by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [8] and initiatives by the Australian government [9], have laid foundational guidelines for incorporating generative AI in education. However, there is a noticeable gap in the use of these frameworks to implement generative AI practically in K–12 educational settings. Specifically, concrete, classroom-level guidance is needed to empower teachers and facilitate learners in harnessing the full potential of generative AI tools.

In K–12 education settings, generative AI presents opportunities to enrich the educational experience by facilitating self-regulated learning (SRL). SRL is essential for cultivating lifelong learners who can adeptly navigate the evolving challenges of the 21st century [10]. It equips students with the abilities to thoughtfully engage in their academic journey, set goals, strategically approach learning tasks, and reflect critically on their learning experiences. Once integrated into K–12 education, generative AI can engage students in learning by writing interactive prompts to acquire domain-specific knowledge. Generative AI tools (e.g., ChatGPT) can provide tailored learning experiences, and real-time feedback to meet the needs of individual students [4], [7].

Therefore, it is imperative to address the pedagogical needs in K–12 education settings. Increasingly, traditional models of teaching and learning are perceived to inadequately prepare students for the complexities of an AI-infused society [2]. There is a pressing need to propose pedagogical models that can effectively integrate generative AI tools in K–12 settings for the betterment of students to meet the demands of contemporary and future AI-permeated societies [11].

This article introduces a comprehensive framework for learning and teaching through the integration of generative AI tools into K–12 education. The framework was developed collaboratively by researchers and practicing teachers. The purpose of the framework is to equip students with the necessary skills to excel in an era deeply influenced by AI. In addition, the framework seeks to redefine the roles of both teachers and students. Specifically, teachers assume the roles of facilitator and guide in a learning process that is enriched by generative AI tools. Their students are then encouraged to take ownership of their learning and to engage deeply with problem-solving tasks and domain knowledge acquisition. These interactions between students and generative AI tools are set to occur in a supportive environment, where teachers offer guidance and generative AI tools function as engaging partners [12].

In this study, the effects of a 60-h teaching professional programme under this framework were also evaluated with respect to in-service teachers' understanding of how to integrate generative AI into teaching and learning. In addition, the teachers' perceptions of the domains of content knowledge (CK), technological CK (TCK), pedagogical CK (PCK), and technological, PCK (TPACK) were evaluated, along with their perceived ability to design courses using generative AI tools to support students' SRL.

II. Literature Review

A. Current Frameworks for Generative AI in Education

In recent years, research and practice have increasingly focused on the integration of generative AI in educational settings [4], [7]. Various frameworks have been developed to guide educators and policymakers in harnessing the potential of generative AI tools.

UNESCO has led the way in creating AI competency frameworks for both teachers and students, with the goal of fostering a thorough understanding of AI's importance in education. Both frameworks designed for teachers and for students emphasize adherence to human rights, the protection of human dignity and privacy, and the reinforcement of human agency [8]. However, the practical application of these frameworks in everyday educational settings remains challenging. The UNESCO guidelines do not provide detailed, actionable instructions that teachers can readily apply within varied classroom environments.

The Australian Framework for Generative Artificial Intelligence in Schools [13] outlines a set of guidelines tailored to the educational context, namely, teaching and learning; human and social well-being; transparency; fairness; accountability; and privacy, security, and safety. Regarding teaching and learning, the framework's holistic approach is commendable as it addresses several aspects:

1) the reinforcement of educational practices through impactful integration;
2) instructional methods that cultivate a critical understanding of AI;
3) teacher expertise to augment rather than replace human teaching;
4) the development of critical thinking skills to foster intellectual growth;
5) learning designs that prioritize students' needs;
6) the maintenance of academic integrity to guarantee the ethical application of AI in educational settings.

However, this framework may lack the specificity needed for practical application, specifically clear-cut guidance on how to implement AI tools in varied classroom situations. The effective integration of AI into curricula and teaching practices will require detailed strategies [14], which are not provided sufficiently by the current framework.

In addition to these official guidelines, several scholars have proposed frameworks. For example, Su and Yang [15] proposed a theoretical framework, "IDEE," for generative AI in education. Their framework includes steps such as identifying desired outcomes, determining the level of automation, considering ethical impacts, and assessing effectiveness. Yet, this framework does not offer concrete steps for practical implementation in diverse educational settings. Chan [16] developed an AI education policy for higher education and indicated that students in higher education should take an active role in policy. Furthermore, Kong et al. [17] proposed a 6-P pedagogy, comprising a plan, prompt, preview, produce, peer-review, and portfolio-tracking framework, to guide university students' academic writing.

These endeavors reveal a gap in research and an essential need for a K–12-specific framework that aligns generative AI's innovative capabilities with the developmental requirements of younger students. Such a framework should offer clear guidance for implementation across different educational environments, with a focus on centering human needs and perspectives.

B. Generative AI: Empowering Lifelong Learning

Generative AI has catalyzed individualized learning [2], [3], [17]. By ensuring that learning experiences are tailored, generative AI provides a foundation for the continuous engagement and skill development that are essential for sustained educational growth throughout one's life [7], [9]. Chiu's [7] research delves into AI's diverse impacts on education, highlighting four pivotal roles of AI that support the development of lifelong learners. The first role involves using generative AI for personalization, such that tasks are customized to each learner's skill level. However, personalization may cause students to become too dependent on generative AI and take a passive approach to learning [18]. In K–12 education, therefore, it is vital to not only implement generative AI tools but also educate students about the foundational AI technologies, including the concepts of tokens, transformer algorithms, self-attention mechanisms, and embeddings. Students must comprehend these concepts to appreciate AI's capabilities and constraints and thus avoid an excessive dependence on technology.

The second role of AI is its ability to enhance human–computer interactions. Michel-Villarreal et al. [19] found that using AI chatbots can improve students' communication skills [20]. However, it is crucial to supplement human–computer interactions with teacher-led discussions to nurture empathy, emotional intelligence, and understanding, which AI currently cannot provide.

The third role of AI involves providing feedback on students' work. In K–12 education, immediate feedback can help students to quickly identify areas for improvement and understand complex concepts [21]. Nevertheless, teachers should offer in-depth feedback that encompasses the more qualitative facets of students' work, such as creativity and critical analysis. In addition, it is important to recognize that the content generated by AI may lack the nuance and depth of human insights [6], [22].

In its fourth role, AI can increase the engagement of students through prompt-based interactions with generative AI [23]. For K–12 students, continued engagement is vital for nurturing a lasting enthusiasm for learning. Thus, teachers should develop AI-assisted learning scenarios that encourage exploration, spark curiosity, and facilitate interactive learning [20], [24]. Teachers should address specific AI mechanisms, such as tokens, transformer algorithms, and embeddings, in their curricula to improve students' understanding of generative AI.

C. TPACK Framework and Generative AI in Education

The TPACK framework is a vital model for understanding the integration of technology into educational practices [25], [26], [27]. Shulman [25] introduced the concept of PCK, highlighting the importance of teachers' integrated understanding of both the content they teach and the pedagogical methods best suited for delivering this content. Mishra and Koehler [26] introduced technology knowledge (TK), and proposed that effective teaching in the digital age requires an understanding of how technology can be combined with pedagogical methods and CK. The TPACK framework thus consists of three primary forms of knowledge: PK, CK, and TK. It further includes four hybrid forms of knowledge that emerge at the intersections of the primary forms: PCK, technological pedagogical knowledge, TCK, and TPACK [26, p. 1025].

The TPACK framework guides teachers in creating and implementing technology-enhanced learning experiences that are content-specific and pedagogically sound [27], [28]. TPACK reflects the dynamic integration of the technology, content, and instruction knowledge domains. It plays a pivotal role in guiding the contextual application of technology in instructional contexts [26] and is instrumental in cultivating teachers' competency in integrating technology seamlessly into curriculum-specific teaching [27], [29].

Several recent studies have explored teachers' acceptance of generative AI in education using the technology acceptance model [30], [31], [32]. However, teacher development programmes in which TPACK is aligned with generative AI are scarce. Our study concentrates on four dimensions of CK: CK, TCK, PCK, and TPACK. CK underpins students' learning and SRL objectives, TCK explores the affordances of generative AI for SRL, and PCK encompasses lesson planning strategies in which generative AI is integrated to support SRL. TPACK synthesizes all three dimensions into a cohesive strategy for designing student-centered courses that use generative AI to promote SRL in a unit teaching and learning.

To address the noted gap in research, the current study was conducted to support a teacher development programme tailored to integrate generative AI with teaching and learning. The attention, relevance, confidence, and satisfaction (ARCS) model of motivational design principles, developed by Keller [33], was adopted to guide the programme. The four components of ARCS are also crucial to the design of teaching and learning activities in using generative AI for engaging students for SRL development, drawing their attention, making the learning activities relevant to their experience, fostering confident development in using generative AI, and ultimately, enabling satisfaction after the learning process.

D. SRL via Generative AI

Zimmerman's three phases of SRL, namely, forethought, performance, and self-reflection, are essential for guiding students through domain-specific learning processes [10], [34]. The integration of generative AI into a curriculum can enhance each phase of SRL by providing individualized learning materials and immediate feedback that facilitates reflection on learning strategies and outcomes. However, current K–12 educational frameworks lack a systematic approach to integrate TPACK with generative AI and thus foster SRL.

In the forethought phase of SRL, generative AI can be used to analyze students' existing knowledge and learning preferences, enabling the provision of tailored learning goals and resources [35], [36]. This individualized learning aids in establishing intrinsic motivation and strategic planning [19].

During the performance phase, generative AI can provide immediate feedback to empower students to monitor their understanding and quickly adjust their learning strategies [14]. For example, writing prompts can facilitate dialogue with generative AI. However, young learners are still developing their metacognitive and cognitive abilities [37], [38]; accordingly, they may experience frustration or confusion when working with AI. Thus, teachers play a vital role in providing emotional support and motivation to help students to overcome challenges [39].

In the self-reflection phase, students engage in self-evaluation to assess their own performance and reflect on their interactions with generative AI, enabling them to better plan for subsequent learning tasks [40]. This reflection is a key step toward consolidating learning and preparing for the future.

However, the absence of an integrated TPACK and generative AI framework for SRL in K–12 education has left teachers without a clear strategy to harness AI's full potential in promoting SRL. A dedicated framework could guide teachers in effectively combining their pedagogical expertise and CK with generative

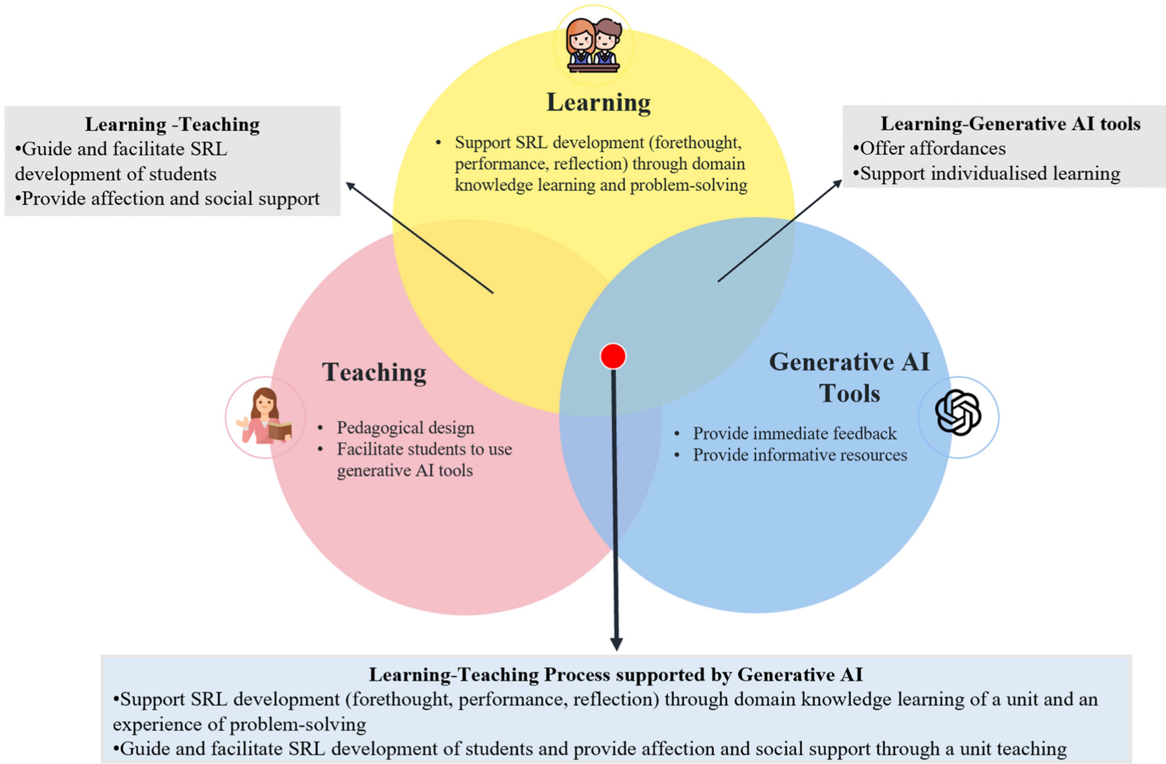

Fig. 1. HCLTF that uses generative AI in K–12 settings.

AI to foster and support SRL. Such a framework would ensure a human-centered pedagogical approach and equip students with the necessary skills and mindset for lifelong learning.

Against this background, a human-centered learning and teaching framework (HCLTF) was proposed in this study. This framework uses generative AI for SRL development through domain knowledge learning in K–12 settings. In addition, a 10-week teacher development programme was introduced to equip in-service primary teachers with conceptual knowledge about generative AI and the skills necessary to use generative AI tools for creating differentiated instructional materials and fostering students' individualized learning.

The programme includes an introduction to generative AI (e.g., concepts of generative AI, tokens, self-attention mechanisms, transformer, supervised and unsupervised learning, and reinforcement learning) and the application of generative AI to course design. The TPACK and ARCS models were integrated to guide the design of the programme. The proposed HCLTF was used to guide the pedagogical design of diverse case studies on subjects, such as Chinese language, English language, mathematics, general studies, and programming. The impact of the teacher professional development programme was examined by addressing the following three questions.

1) To what extent did the teacher development programme improve teachers' comprehension of generative AI concepts?
2) To what extent did the teacher development programme enhance teachers' perceptions of the domains of CK, TCK, PCK, and TPACK?
3) To what extent did the teacher development programme enhance teachers' perceived ability to design courses that would increase students' attention, relevance, confidence, and satisfaction?

III. Proposed Framework

A. Introduction to the Proposed Framework

Fig. 1 depicts the proposed HCLTF. The framework is visually articulated as a Venn diagram composed of three overlapping circles representing the domains of learning, teaching, and generative AI. The following section explains the three domains and the three areas where they intersect.

1) *Learning:* The learning domain, guided by human-centric principles, positions students at the core of the educational experience. It accentuates the facilitation of the three stages of SRL. In this domain, the goal is to empower students to take ownership of their learning process through setting goals, monitoring learning processes, and reflecting on their learning outcomes.
2) *Teaching:* The teaching domain is dedicated to pedagogical approaches that seamlessly integrate generative AI into educational settings. This domain involves guiding teachers to integrate generative AI into their teaching strategies, ensuring that the technology is aligned with pedagogical goals and enhances content delivery. Within this framework, the ARCS model is used to assist teachers in contemplating strategies to enhance students' motivation during the learning process.

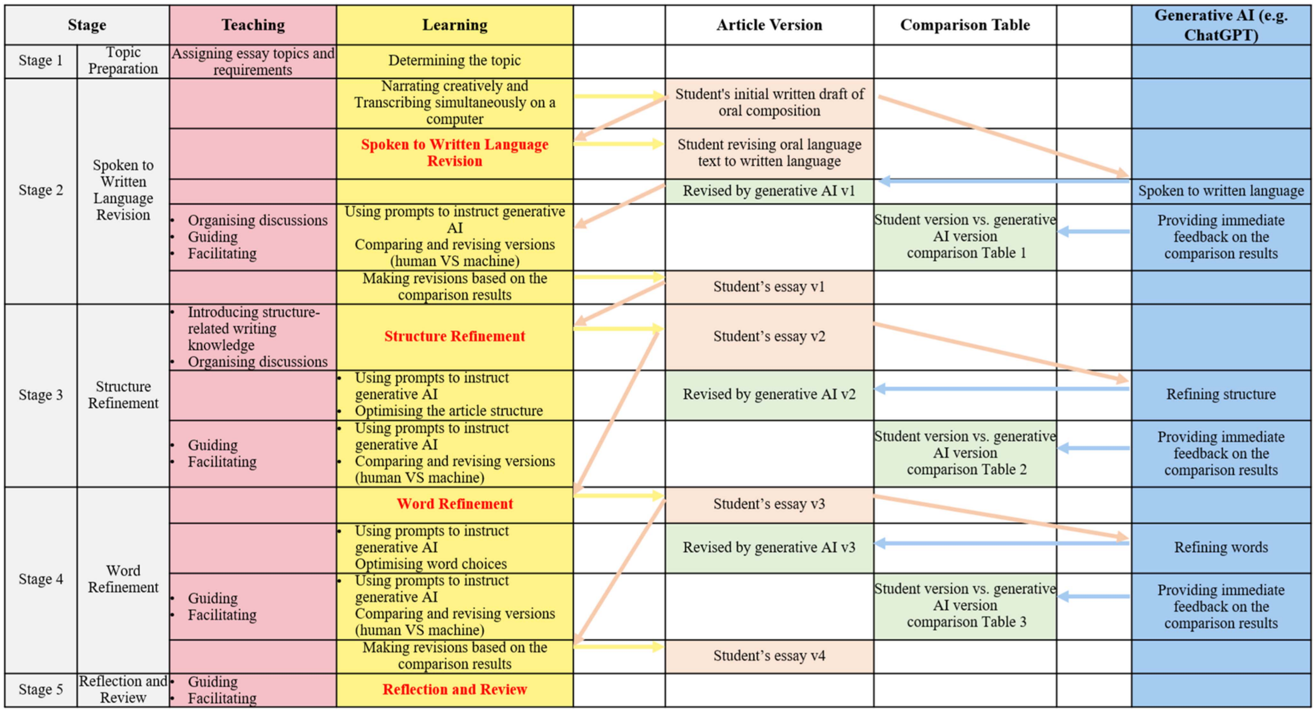

Fig. 2. Five stages of primary grade five students' Chinese writing underpinned by the proposed framework.

3) *Generative AI:* The generative AI domain is focused on providing technological affordances and immediate feedback. In this context, generative AI is a tool that can be used to offer individualized feedback to students.
4) *Learning–Teaching:* At the nexus of the learning and teaching domains, the focus shifts to teachers' guidance and facilitation roles. Teachers are instrumental in steering students through the SRL process by providing affective and social support to foster a supportive learning environment [41].
5) *Learning–Generative AI:* At the intersection of the learning and generative AI domains, neuroscience-informed educational implications are used to enhance attention, engagement, error-feedback, and reflection and thus support students' SRL [42]. Accordingly, students are encouraged to actively find and correct errors in the content generated by AI.
6) *Central Zone—Learning, Teaching, and Generative AI:* The central zone, where all three domains converge, symbolizes the unified essence of teaching and learning. This should be a synergistic space, where the framework domains are combined to create a cohesive and dynamic learning environment that supports SRL and prepares students for the demands of the 21st century.

B. Case Study: Generative AI Tools as Partners for Enhancing Primary Students' Chinese Writing

This case study demonstrates the application of the HCLTF for designing learning and teaching activities in using generative AI (e.g., ChatGPT) for supporting Grade 5 students' Chinese writing in Hong Kong, in which students are guided by their teachers to partner with ChatGPT across a five-stage lesson plan comprising topic preparation, spoken to written language revision, structure refinement, word refinement, and reflection and review (see Fig. 2).

1) *Stage 1—Topic preparation:* In this stage, the teacher assigns essay topics and clearly explains the expectations. Students engage in goal-setting and planning their essays. In this stage, generative AI has not yet been introduced.
2) *Stage 2—Spoken to written language revision:* The teacher facilitates discussions and guides students in the process of brainstorming ideas orally [43]. Students create drafts of their essays by verbally articulating their thoughts and converting them to text using tools, such as Google Docs, which support speech-to-text functionality. The students then refine their spoken language drafts to align with written language standards by removing colloquialisms and replacing them with more formal language and adding correct punctuation. Next, the students use ChatGPT to revise their spoken language drafts into a more formal written language (Version 1). They learn to interact with the AI interface through prompts, compare their work with the AI's output, and resolve the differences. A comparison table is created to contrast the student version with the generative AI version 1 (v1) and thus provide immediate feedback on the outcomes. Throughout this stage, teachers' scaffolding provides crucial support.
3) *Stage 3—Structure refinement:* At the beginning of this stage, the teacher introduces structural knowledge and organizes further discussions to deepen the students' understanding of essay structure. The students apply this

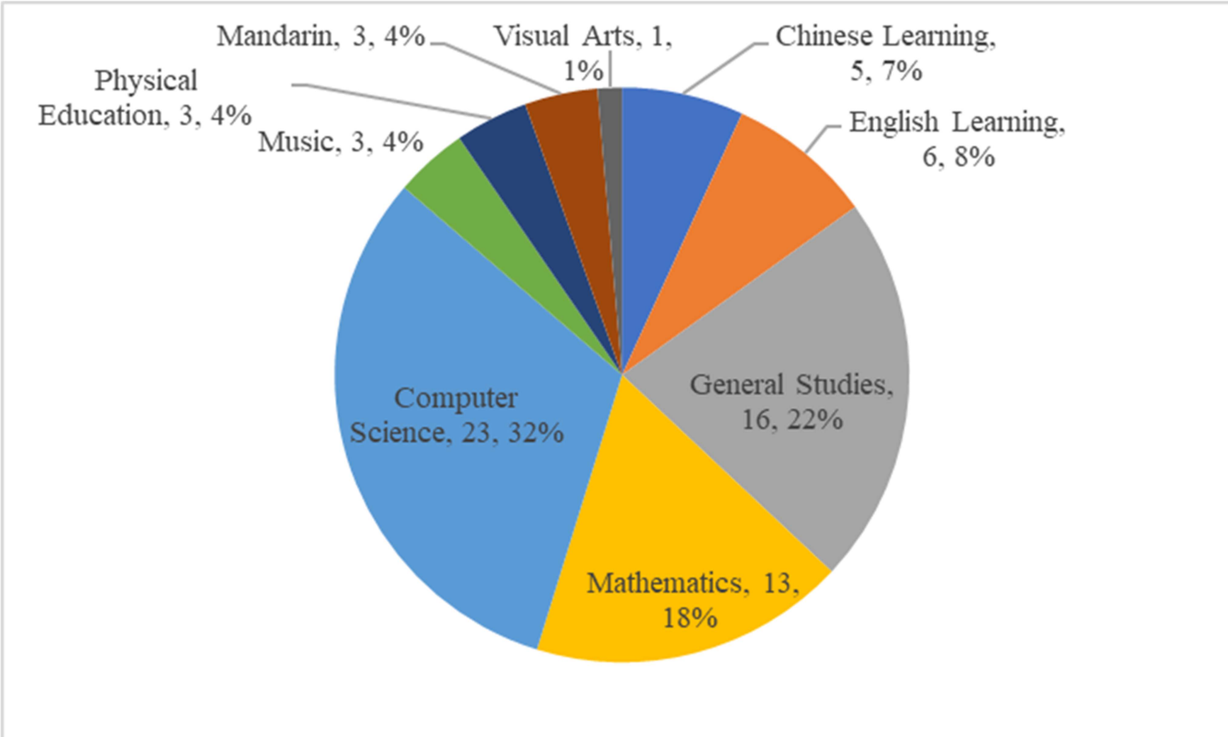

Fig. 3. Distribution of subjects taught by teachers.

knowledge to enhance the organization of their essays, considering elements, such as introductions, transitions, and conclusions. After an initial student-led revision, generative AI tools are used to further refine the structure (v2). The students are encouraged to critically and comparatively evaluate the structure proposed by ChatGPT against their own essay, and teacher-led discussions are used to consolidate the learning points from prior revisions.

4) *Stage 4—Word refinement:* This stage focuses on linguistic precision. The teacher continues to provide guidance and to facilitate the refinement of language and word choice. The students focus on enhancing the phrases and terminology used in their essays. Subsequently, they can ask ChatGPT to integrate advanced rhetorical devices, such as metaphors or personification, into their writing. Finally, they compare their revisions with ChatGPT's suggestions (v3) to determine the most effective expression.

5) *Stage 5—Reflection and review*: In this stage, the teacher facilitates a discussion to enable reflection, comments on the students' essays (v4), highlights areas of strength, and suggests improvements. The students summarize their learning experiences and the knowledge and skills gained throughout the cycles of interaction with ChatGPT.

In the proposed framework, generative AI is used as a tool to support and enhance the writing process, from initial topic preparation to the final reflection. In each stage, learners are encouraged to actively engage with domain knowledge. As a result, the learners continuously refine their understanding. This iterative process of learning and application is fundamental for the development of SRL competencies.

IV. Research Design

This study is part of a larger project that aims to empower in-service K–12 teachers by integrating generative AI into course designs. In this mixed-methods study, both quantitative and qualitative data analyses were adopted.

A. Participants

The study recruited a cohort of 31 in-service primary school teachers. A purposeful sampling technique was used. During the recruitment process, the researchers contacted the principals of several local primary schools and extended invitations to teachers who expressed interest in participating in the teacher development programme.

The gender distribution of the participants was nearly equal, with 16 female and 15 male teachers. Regarding educational attainment, most of the participants held a bachelor's degree ($n = 21$); the others possessed a master's degree ($n = 10$).

The participating teachers were responsible for teaching two or more subjects. Fig. 3 presents the subject distribution among the participants: computer science was most commonly taught, followed by general studies, mathematics, and languages.

B. Procedure

The teachers were invited to participate in a six-week programme that included: 1) a 30-h course intended to a foundational understanding of AI (e.g., what AI is, the five steps of machine learning, supervised learning, and unsupervised learning) and deep learning (e.g., data cleaning, data augmentation, neural networks, computer vision, convolution neural networks, and recurrent neural networks), and generative AI concepts and 2) a 30-h course on integrating AI into course design in areas, such as Chinese language, English language, mathematics, general studies, computer science, and music education.

Throughout the programme, the teachers completed a series of assessments to gauge their progress and the efficacy of training. These assessments included pr-etest and post-test to measure their understanding of AI concepts and evaluate their knowledge of TPACK before and after the course and their self-perceived competency in designing courses, specifically in terms of increasing students' attention, relevance, confidence, and satisfaction.

In the final week of the programme, the teachers were required to write a self-reflective piece on their experiences and the insights gained from learning about the use of generative AI tools in education.

C. Data Collection and Analysis

1) Data Collection: The data sources included AI concept tests, questionnaires, and reflective writing.

a) Pre-AI and post-AI concept tests: The test consists of ten multiple-choice items. It was designed by authors to assess teachers' understanding of tokens, self-attention, embeddings, transformer, prompting engineering, other basic AI concepts, and the implications of generative AI. The Cronbach's alpha value for the test exceeds 0.6, indicating a moderate level of consistency in the measurement of conceptual understanding of AI [46]. An example item from the test is provided below.

Which of the following is correct about tokens in the context of large language models?

1) Tokens are the smallest units of text that a large language model can process.
2) The number of tokens in a large language model directly corresponds to the number of words.
3) Tokens can represent words, parts of words, or punctuation.

a) (1) and (2) only
b) (1) and (3) only
c) (2) and (3) only
d) All of the above.

b) Pre-survey and post-survey on TPACK: This survey was designed to assess changes in the teachers' self-evaluated knowledge in the TPACK domain. Specifically, it aims to measure changes in the teachers' perceived abilities to use text-based generative AI tools for differentiated instructions and to address learner differences. This instrument was adapted from previously validated instruments [27], [28]; the responses are scored on a five-point Likert scale, with options ranging from 1 (strongly disagree) to 5 (strongly agree). The survey encompasses 14 items across four constructs: CK, with three items focusing on prompt engineering knowledge (e.g., "I have various ways and strategies of refining prompts when using generative AI tools."); PCK, with four items focusing on addressing individual differences using generative AI (e.g., "I can guide my students to use generative AI tools through the problem-solving process."); TCK, with four items focusing on understanding the technological aspects of generative AI (e.g., "I understand the importance of transformer architecture in determining the effectiveness of generative AI tools."); and TPACK, with three items focusing on the integration of teaching and technology (e.g., "I can teach lessons that appropriately integrate prompt engineering, generative AI tools, and teaching approaches."). The reliability of the survey is substantiated by the Cronbach's alpha values for the four constructs of the pretest and posttest, which range from 0.75 to 0.92. These values demonstrate a high level of internal consistency, indicating that the survey items consistently reflect the constructs they are intended to measure [46].

c) Pre-survey and post-survey on assessing teachers' ability to use text-based generative AI tools for teaching from the perspective of ARCS: This survey was developed to measure the changes in teachers' perceived abilities to create teaching materials and guide students to increase their attention, relevance, confidence, and satisfaction. This instrument, which was adapted from previous studies [44], [45], uses a five-point Likert scale for responses, with options ranging from 1 (strongly disagree) to 5 (strongly agree). It encompasses 12 items across four constructs: attention, with three items assessing teachers' perceived ability to design engaging learning materials using generative AI tools (e.g., "I can use generative AI tools to design teaching materials and activities to sustain students' interest."); relevance, with three items assessing the creation of learning experiences that are personally meaningful to students (e.g., "I can use generative AI tools to create authentic scenario-based learning activities to allow students to relate the learning content to their own life experiences."); confidence, with three items on helping learners to believe and feel that they will succeed and to improve their confidence in using generative AI (e.g., "I can guide students to use generative AI tools to seek multiple answers and thus enhance their confidence through multi-perspective learning."); and satisfaction, with three items on guiding students to use generative AI tools to seek multiple answers to enhance their satisfaction through multi-perspective learning (e.g., "I can guide students to use generative AI tools to solve problems and develop their independent thinking, allowing them to experience a sense of achievement in their learning."). The Cronbach's alpha values for the four constructs of the pretest and posttest exceed 0.85, indicating good internal consistency [46].

d) Reflective writing: The teachers were asked to provide written reflections in either English or Chinese throughout framework implementation in the programme. They documented the challenges encountered, the strategies used, and their overall impressions of the usefulness of the generative AI tools for enhancing students' SRL in practice.

2) Data Analysis: This study employed a mixed-methods approach, integrating both quantitative and qualitative analyses to comprehensively evaluate the effectiveness of the teacher development programme. The Shapiro–Wilk test was applied to assess the normality of the data pertaining to the first and third research questions. The results indicated that the data were normally distributed ($p > 0.05$). Consequently, the paired sample t-test was applied to analyses of these data, as this test is well suited for comparing the means of two related groups when the data are normally distributed. Furthermore, the self-reflective writings were analyzed to triangulate the quantitative data. The second research question focused on the effect of the programme on teachers' TPACK. The Shapiro–Wilk test was applied to the data and revealed a nonnormal distribution. Thus, the paired-sample Wilcoxon test was used to evaluate the effect of the programme on teachers' CK, PCK, TCK, and TPACK. This nonparametric alternative test was selected as the most appropriate method to evaluate the data, as it does not assume a normal distribution and is robust when applied to ordinal data or skewed distributions.

V. Results

A. Effect of the Teacher Development Programme on Concept Test Scores

The mean differences between the preconcept and postconcept tests. The assumption of normality was not violated (Shapiro–Wilk test, $p > 0.05$). The pretest score ($M = 3.581$, $SD = 1.205$) was lower than the posttest ($M = 4.871$, $SD = 1.648$; paired-samples t-test), and this difference was significant, $t(30) = 3.616$, $p < 0.001$, 95% confidence interval (CI) [0.562, 2.019]. The results show that the teacher development programme had a positive effect on the teachers' understanding of the AI concepts.

B. Effect of the Teacher Development Programme on TPACK Evaluation Scores

Table I shows the descriptive statistics of teachers' perceptions of TPACK. A Wilcoxon signed-rank test showed that the teacher development programme led to statistically significant increases in the teachers' CK ($Z = –4.562$, $p < 0.001$), PCK ($Z = –4.632$, $p < 0.001$), TCK ($Z = –4.396$, $p < 0.001$), and TPACK ($Z = –4.561$, $p < 0.001$).

These results reveal that the teacher development programme was highly effective in enhancing teachers' knowledge and skills across the CK, PCK, TCK, and TPACK domains. The statistically significant improvements in the survey scores suggest that the programme increased not only the teachers' theoretical understanding of the integration of technology with pedagogy and content but also their ability to apply this knowledge in practice.

To triangulate the quantitative data, the teachers' self-reflective writings were analyzed, and some examples were selected.

1) CK
   a) The course provides information on AI, which can be passed on to students, and emphasises the importance of understanding AI in education. (T1)
   b) This course has really opened my eyes to the role generative AI can play in our classrooms. It is not just another buzzword; it is a tool we can use to really make a difference in how we teach and how our students learn. I will pass on what I have learnt about AI to my students and help them understand its growing importance in our world. (T17)
2) PCK
   a) There is a need to deepen teachers' understanding of AI to facilitate the birth and transformation of pedagogy. I learnt a lot from this course. (T23)
   b) After taking this programme, I see the power AI has to reshape [how] we teach. I have gained so much insight into how AI can help tailor our teaching methods to each unique student. The framework we have been introduced to is very practical. It underscores the importance of keeping our students at the heart of their learning journey. By harnessing the power of AI, we can create a learning environment that not only recognises but also celebrates each student's individual needs and potential. (T16)
3) TCK
   a) Words like "tokens" and "transformers" were foreign to me, and I was worried that machines might take our jobs. But this course showed me that is not the case. (T14)
4) TPACK
   a) Integrating AI into our teaching is not just about understanding the technology or the content. I have learnt that using AI tools effectively requires a careful balance. This course has given me the confidence to strategically use AI in my lesson plans. (T29)
   b) AI can give me insights into where a student might be struggling, allowing me to intervene with the right kind of support at the right time. The TPACK framework reminds me that technology is a tool to facilitate this journey, not the journey itself. My role is to use that tool to build a bridge between students' current abilities and their potential, guiding them towards becoming lifelong, self-motivated learners. (T15)

TABLE I
Descriptive Statistics of Teachers' Perceptions of TPACK

	M	SD	Z	*p*
Post-CK	4.258	.588	–4.562	*< 0.001*
Pre-CK	3.301	.663		
Post-PCK	4.234	.602	–4.632	*< 0.001*
Pre-PCK	2.952	.823		
Post-TCK	4.258	.614	–4.396	*< 0.001*
Pre-TCK	3.218	.939		
Post-TPACK	4.215	.636	–4.561	*< 0.001*
Pre-TPACK	2.774	.908		

C. Effect of the Teacher Development Programme on Perceived Ability to Teach With Generative AI Under the ARCS

Statistically significant mean differences in attention, relevance, confidence, and satisfaction between the presurvey and postsurvey were assessed (paired samples t-test). The assumption of normality was not violated (Shapiro–Wilk's test, $p > 0.05$). Table II tabulates the descriptive data on teachers' perceived ability to use generative AI to design courses that can increase students' attention, relevance, confidence, and satisfaction.

TABLE II
DESCRIPTIVE STATISTICS OF TEACHERS' PERCEIVED ABILITY TO DESIGN COURSES UNDER ARCS

	M	SD	SE	*t*	*p*
Post-Attention	4.366	.598	.107	7.762	< 0.001
Pre-Attention	3.151	.950	.171		
Post-Relevance	4.226	.669	.120	8.161	< 0.001
Pre-Relevance	3.000	.878	.158		
Post-Confidence	4.333	.644	.116	7.652	< 0.001
Pre-Confidence	3.108	.900	.162		
Post-Satisfaction	4.366	.663	.119	6.966	< 0.001
Pre-Satisfaction	3.290	.811	.146		

For attention, a statistically significant increase was observed from the presurvey (M = 3.151, SD = 0.950) to the postsurvey (M = 4.366, SD = 0.598), t(df) = 7.762, $p < 0.001$. The effect size was large (Cohen's d = 0.87). For relevance, the participants reported a significant improvement from the presurvey (M = 3.000, SD = 0.878) to post-survey (M = 4.226, SD = 0.669), t(df) = 8.161, $p < 0.001$. The effect size was large (Cohen's d = 0.84). For confidence, there was a significant increase from the presurvey (M = 3.108, SD = 0.900) to the post-survey (M = 4.333, SD = 0.644), t(df) = 7.652, $p < 0.001$. The effect size was large (Cohen's d = 0.89). For satisfaction, there was a significant increase from the presurvey (M = 3.290, SD = 0.811) to the post-survey (M = 4.366, SD = 0.663), t(df) = 6.966, $p < 0.001$. The effect size was large (Cohen's d = 0.86).

To add depth to the quantitative data, the teachers' self-reflective narratives were carefully reviewed.

1) Attention

a) The training transformed my lesson kick-offs. I now use targeted questions that tap into students' curiosity, leading to a noticeable boost in their participation from the start. (T16)

b) After completing the programme, I have noticed a marked change in the way I approach the start of my lessons. This shift became evident when I observed my students more eagerly participating in discussions and activities right from the beginning of class. Generative AI can give me many amazing ideas. (T24)

2) Relevance

a) I am always striving to make my lessons relevant, but the programme gave me a new perspective on how to integrate real-world problems into my curriculum. By using AI to brainstorm real-time scenarios, I am able to bring context to theoretical concepts. (T29)

3) Confidence

a) After the first day of this programme, I encouraged students to converse with generative AI and critically evaluate its responses. They were developing critical thinking skills by identifying areas where AI's responses can be improved. (T8)

4) Satisfaction

a) Integrating generative AI into my daily teaching practices has brought a new level of joy as I watch students take ownership of their learning. The changes I have implemented in the course, inspired by what I've learnt from this teacher development programme, have been met with enthusiastic feedback from students, affirming the value of these innovative tools in enhancing their educational experience. (T23)

VI. DISCUSSION

In this study, a framework was proposed to integrate generative AI tools into the HCLTF to guide in-service teachers' practices. The results of the study show that teacher development programme significantly increased the in-service teachers' conceptual understanding of generative AI, improved their pedagogical strategies, and enhanced their perceived ability to integrate the AI tools into curriculum design. These findings align with the emerging consensus on the importance of providing professional training for in-service teachers in the age of generative AI in previous research [31], [48], [49].

First, by learning the theoretical underpinnings and practical uses of generative AI, teachers gain deeper insights into the principles and the limitations of large language models. For instance, the concept of embeddings, which are the high-dimensional vector spaces where lexical items are mapped to capture semantic significance, is pivotal to the operational capacity of generative AI models to process natural language. Thus, ChatGPT demonstrates proficiency within the domain of linguistic tasks, but its ability to handle abstract reasoning tasks, such as mathematical problem-solving, is constrained. In addition, techniques, such as few shots, enable teachers to produce a variety of similar questions. This capability can be particularly useful when constructing assessments.

Second, the programme helped the teachers to shift from traditional educational paradigms to new models that use AI for differentiated instruction. This enabled them to become facilitators of knowledge and of students' SRL [50].

Finally, the teachers noted an improved capacity to design courses that can enhance students' attention, relevance, confidence, and satisfaction, suggesting that the teacher development programme equipped them with strategies and tools to make learning more engaging and meaningful for their students. By incorporating generative AI into their teaching, teachers can enhance students' motivation, which in turn can foster SRL.

The results of the study contribute to the ongoing dialogue between researchers and in-service teachers on educational innovation. The proposed HCLTF can guide future K–12 practitioners. The HCLTF, which was inspired by TPACK, provides an integrated understanding of how generative AI, pedagogy, and content can interact to create student-centered learning experiences.

The findings of this study have three implications for research and practice in the area of integrating generative AI into K–12 education settings.

First, the results of this study can inform researchers and designers about the need for practical and actionable frameworks to guide the integration of generative AI into teaching practices [15], [47]. This framework contributes to the ongoing dialogue on educational innovation and highlights the importance of developing adaptable models that can guide K–12 practitioners in the future [49], [51].

Second, this study underscores the importance of human-centered principles when integrating generative AI into the classroom [9], [13]. The results suggest caution against an over-reliance on AI technologies and support the teacher's role as a social and emotional anchor in the learning process. This human-centered approach ensures that the essential human aspects of learning and teaching, such as empathy, ethical considerations, and social interactions, are maintained and strengthened.

Finally, for curriculum developers and EdTech stakeholders, this study highlights the potential of generative AI when it is integrated thoughtfully and ethically into K–12 education settings. The results suggest an opportunity to design curricula that use AI not only to assist teachers in creating differentiated instruction but also to cultivate students' SRL capabilities. Furthermore, EdTech stakeholders are encouraged to collaborate with teachers to create tools that align with the HCLTF, thus ensuring that technology supports educational goals without overshadowing the human elements of teaching and learning.

VII. Conclusion

Currently, a transformative shift is occurring in education: generative AI tools and enhanced AI literacy are empowering educators to refine their pedagogical strategies. The results of this study contribute to the ongoing dialogue between researchers and in-service teachers on educational innovation. The proposed HCLTF can guide future K–12 practitioners. The findings of this study call for continued research and dialogue among researchers, practitioners, curriculum developers, and EdTech stakeholders to ensure that generative AI is incorporated in a way that enhances learning while remaining grounded in human-centered educational values.

The study also has three notable limitations. First, although the HCLTF was co-designed by researchers and in-service teachers and has been applied to the design of courses in Chinese language, English language, mathematics, general studies, computer science, and music education, its applicability to other subjects and the effects on students remain unknown. As such, the framework may not be fully representative of or adaptable to the diverse range of scenarios encountered in primary and secondary education settings. Further iterations and validation across a variety of educational environments and disciplines are necessary to ensure the HCLTF's robustness and generalizability.

Second, the participants in this study were limited to in-service primary teachers. A more diverse group of teachers with different levels of AI experience and expertise in various subjects will be invited to participate in future studies. In the future, research should consider how school culture influences the adoption and effectiveness of AI in teaching. A three-level analysis could be adopted to assess the dynamics between teacher–student interactions, teacher–teacher interactions, and the overall school environment. By expanding the participant pool and examining additional factors, future research may provide a generalizable understanding of the proposed HCLTF.

Finally, the study primarily focused on the perspective of teachers, with less emphasis on the student experience. Future research should include students' voices to understand how the integration of generative AI affects their learning experience, engagement, and outcomes [16]. Students' feedback should be used to iterate and improve the framework for integrating AI into learning and teaching practices in K–12 settings.

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