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Development of Computational Thinking through Adaptive Gamification and Learning Analytics to Enhance Science Education: A TPACK-Based Professional Development Program and Adaptive Environment Methodology

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Abstract

The development of Computational Thinking (CT) offers a powerful approach to enhancing science teaching in preschool and primary education. However, this requires well-trained teachers who can navigate complex technological environments. This study describes the methodology and design of an adaptive gamification environment designed to equip pre-service teachers with essential CT competencies. Integrated into a professional development program grounded in the Technological Pedagogical and Content Knowledge (TPACK) framework, the environment utilises a custom application that adapts game mechanics and content to users based on the Hexad player model. The methodology unfolds in two distinct stages. Firstly, participants engage with the four CT concepts through problem-based gamified activities unrelated to programming, employing AI-driven intelligent NPCs to personalise the learning experience and link these concepts to science education. The second stage utilises a "play-modify-create" approach within a block-based programming environment. Teachers apply the "to play, to think, to code" pedagogy by analysing finished programs, decomposing logic, and transforming plans into code through testing. Crucially, the system provides real-time learning analytics to the teacher educator throughout both stages. This data equips educators to monitor progress and assist them with greater precision, effectively utilising educational data in technology-rich settings.

Keywords: *Computational Thinking; Early and Primary Teacher Education; Adaptive Gamification; Learning Analytics; TPACK model*

1. Introduction

In the rapidly evolving landscape of the 21st century, in this rapidly evolving digital and AI era, digital competency and computational thinking (CT) skills have become fundamental required skills on an equal level with reading or writing, and not just for computer scientists, but for all individuals [1, 2, 3]. CT has started been integrated into K-12 curricula in educational systems across Europe and globally, as it has been recognised as an effective approach for analysing and solving problems beyond programming, across disciplines, and particularly in mathematics and science education [2, 4]. However, despite the acknowledged need for these skills, their practical implementation poses significant challenges. One of the primary obstacles is the lack of specialised teachers capable of utilising CT effectively in education and with the necessary confidence, as in many cases, the vast majority of teachers have no prior CT [5].

The development of CT and its integration into science education could benefit substantially from a shift away from the traditional "one-size-fits-all" learning approach, which often fails to address the diverse learning paces, habits, and needs of individual students [6]. Over the last few years, educational technology has become more widely available and has pivoted towards more adaptive learning and gamified environments. These methodologies utilise motivational theories, gaming elements, personal data, and algorithms to personalise the learning experience, tailoring content delivery to student performance and engagement [7, 8]. While promising, adaptive gamification remains in an early stage, particularly with respect to specific content, such as CT development or science education, and to stable adaptation criteria [9].

The role of teachers is undergoing significant change, shifting toward providing strategic support for students to promote self-directed learning [10]. Consequently, there is a need to re-evaluate teacher professional development standards [11] to enhance teacher training and develop critical skills, such as digital literacy, scientific inquiry, and collaborative problem-solving [12, 13]. The use of Learning Analytics (LA) can serve as a key tool in monitoring the teachers' engagement and progress and allow

for accurate, data-driven interventions that support teachers precisely when they encounter difficulties, increasing the effectiveness of the training while minimising unnecessary disruptions to their learning process [14, 15, 16].
Consequently, this paper introduces the methodology and content of the proposed adaptive gamification environment, detailing its specific functionality, adaptive mechanisms, and content. Moreover, the study explains how the adaptive gamification environment is interconnected with a dedicated application that is fed by Learning Analytics, enabling data-driven insights into the learning process. It also introduces the structure of the teachers' professional development program, grounded in the TPACK framework and a pedagogical model that promotes gracefulness and engagement.

2. Architectural Framework

The integration of Computational Thinking (CT) into preschool and primary science education offers a transformative approach to developing problem-solving skills [2]. However, for this integration to be successful, teachers must possess not only technical skills but also pedagogical capabilities to navigate complex technological environments [17]. To address this, we propose a custom-built adaptive gamification environment based primarily on the architectural suggestions of Zourmpakis et al. [9], with a focus on CT development and enhanced by the "play-modify-create" general approach and the use of Learning Analytics (LA). This system aims to move beyond the "one-size-fits-all" approach by leveraging the core psychological needs of self-determination theory and the Hexad player-type typology, and by adapting game mechanics and elements based on the user's specific player profile, choices, and needs. However, in this case, as the primary learning content is the development of CT skills and their use in science education, there would be no adaptation of learning strategies; instead, a solely problem-based learning strategy would be used, given CT's close relationship to problem solving [2]. Also, this new system is developed using the Unity3D game engine.
To be more specific, this specific framework revolves around a dual-loop system:
(a) The Player: The user interacts with the system, and the system adapts game elements (e.g., points, badges, narrative depth, difficulty, etc.) based on their Hexad player profile and choices.
(b) The Instructor: A parallel Learning Analytics (LA) dashboard collects real-time data, allowing the teacher educator to monitor progress and decide when and how to intervene precisely when trainees face misconceptions or technical difficulties.

2.1 User Modeling and Adaptation Process

The core of the environment's adaptability lies in the Hexad Player Model. Following the suggestions of Zourmpakis et al. [9], upon initialising the application, users complete a validated 24-item questionnaire. The system analyses the results to categorise the user as a dominant player type, while also acknowledging secondary traits from the next two player types. This distinction is critical because, as noted in the literature, users rarely fit into a single category/player type and also have minor traits from other types.
Within the Hexad typology, there are 6 player types, each with a distinct motivational focus/origin. The player types are:

- The Achievers: Motivated by competence. The system adapts by offering distinct challenges, progress bars, and mastery-based badges.
- The Players: Motivated by extrinsic rewards. The system emphasises points, virtual currency, and a visible reward loop.
- The Philanthropists: Motivated by purpose. The system adapts the narrative to emphasise helping Non-Player Characters (NPCs) and unlocking content that benefits the "game world."
- The Disruptors: Motivated by change. The system offers opportunities to test boundaries and provides non-linear pathways where possible.
- The Socialisers: Motivated by relatedness. While the current build focuses on single-player RPG elements, the system emphasises interactions with NPCs and narrative connections.
- The Free Spirits: Motivated by autonomy. The system reduces linear hand-holding, opening up the map for exploration and self-directed discovery.

The adaptation methodology employed here is dynamic and unfolds across three distinct layers. The process begins with an initial configuration in which the interface and reward mechanisms are set according to the user's dominant Hexad type. For instance, a user identified as an "Achiever" type will be presented with points and the ability to collect badges, which they could equip on their character to leverage their extrinsic motivation, whereas a "Socialiser" will encounter a more minimal interface that prioritises additional interactions with NPCs, additional narrative information, and/or assisting others. Following this, the system tracks students' time, errors, responses to AI NPCs, and indirect questions about difficulty and game elements during gameplay. Indirect questions are used only for player profile adaptation, with the exception of questions regarding difficulty, which are also used to adjust the environment and pace at runtime. Changes to the environment and/or the pace of the learning scenario may also occur during gameplay due to students' errors and/or persistent incorrect responses to AI NPCs. In the latter case, the AI NPCs will adjust their responses and intervene, initially indirectly and later more directly, with scaffolded hints to prevent frustration or disappointment. However, if a user progresses too rapidly, the system doesn’t provide hints to ensure the challenge level remains engaging. However, all tracked data, along with students' dominant player types, are provided to the LA Dashboard for instructors' use, except for the indirect questions.

2.2 The Role of AI NPCs

A distinct innovation in this adaptive gamification environment is the integration of AI NPCs (Non-Player Characters). Unlike traditional NPCs that rely on static dialogue trees, these agents utilise AI to act as intelligent scaffolds [18]. These NPCs serve two primary functions within the learning experience. Firstly, they make the dialogue feel more natural and less static, responding to the player in a manner that remains within their role and the scenario's constraints. Moreover, they serve as assessors and feedback providers most of the time, acting as judges or advisors on users' solutions (Figure 1). For example, in a task requiring the decomposition of a treasure map route, the NPC evaluates the user's step breakdown and provides natural-language feedback, guiding them toward a more granular decomposition if the initial attempt is insufficient. However, all AI NPCs have strict boundaries on their roles and the answers they can give, set through script coding. In this alpha model, the system uses the Gemini 2.5 Flash model via the API, which requires that liability statements be signed to ensure compliance with student data protection regulations. However, to overcome these barriers and ensure data security and sovereignty, we propose transitioning to locally hosted servers. Specifically, to deploy an open-source Large Language Model (LLM), such as DeepSeek, Qwen 2.5, or Gemma 2, on local servers. In this way, the local deployment ensures that no student interaction data leaves the university's network, effectively eliminating third-party data privacy risks and eliminating the need for external liability agreements.

Fig. 1. Interaction with AI NPC

2.3 Content Design: Linking CT to Science Education

The curriculum within the application is strictly sequenced to ensure mastery, beginning with non-programming conceptual tasks [3, 19] that gradually link to scientific inquiry. The introductory phase begins with the "Peanut Butter and Jam Sandwich" activity, in which users must instruct an AI NPC to make a sandwich. The NPC follows instructions literally; for instance, if not told to use a knife, they use their hand to take the peanut butter, to highlight the necessity of precise, step-by-step algorithmic thinking. Following this introduction, the learning content is divided into four modules, each using problem-based learning and containing an explicit science-related phase in which the CT concepts are applied to science education contexts.

In the first module, focused on abstraction, the user must plan a party by filtering out irrelevant details, such as napkin colours, to focus on key constraints, such as budget and time. This lesson then transitions to circuit design, where users learn that using standard symbols for batteries and bulbs is an abstraction that reduces visual noise and focuses on system function. The second module addresses decomposition through a task in which users design a treasure hunt, breaking a complex route into sequential steps. This concept is then applied to troubleshooting a system, in which users disassemble a malfunctioning electrical circuit or mechanical toy into components to test them individually. The third module explores pattern recognition, engaging users in puzzles that require them to identify visual and logical patterns. Towards the end of the lesson, this concept links directly to science observation, testing, and drawing conclusions, such as analysing shadow lengths at different times of day to recognise solar movement or testing materials with a magnet to identify patterns of attraction. Finally, the fourth module covers algorithmic thinking, in which users apply strict "if-then" logic to model everyday decisions and debug cooking recipes. This connects to experimental design, teaching users that a science experiment requires a strict algorithm to ensure validity, such as changing only one aspect, such as the angle of the ramp or the weight of the car, and keeping all others constant when testing the car’s speed down a ramp.

2.4 Learning Analytics Dashboard

A vital component of the learning process is the LA dashboard, accessible to the instructor during gameplay. This dashboard visualises the progression and choices of all students, apart from their indirect answers regarding game elements, mistakes, time, and dominant player types, allowing for immediate broad or individual interventions and tailoring their in-person language, for example, using more competitive phrasing if the class comprises many “Achievers” or “Players.”

Regarding technical implementation, the LA data and dashboard rely on the Client-Server-Client model. To be more specific, the adaptive gamification application (client) serialises the data as JSON and sends it to the Firebase Cloud using the Firebase Unity SDK, without requiring a separate API server. The data is then returned to another simple UI application on the instructor’s tablet. The application is also made with Unity3D.

3. Tpack-Based Professional Development Program

The professional development (PD) program will be grounded in the Technological Pedagogical Content Knowledge (TPACK) framework [20, 21]. Teachers are often found to have significant gaps in teacher preparation regarding science education and digital innovation. They appear to struggle to integrate advanced digital tools into inquiry-based learning, which leads to a reluctance to adopt innovations and a lack of confidence and methodological grounding [22, 23]. Consequently, relying solely on technical training or the application of LA is insufficient to design engaging, student-centred learning experiences that will move teachers beyond isolated technical training [24]. By illuminating the dynamic interplay between technology, pedagogy, and content, such as the TPACK framework [20], and following a model that guides teachers from intuitive exploration of the concepts to decomposing logic, testing what they learned, critically analyzing their learning, and connecting it to concrete scientific practices, such as the “To Play, To Think, To Code, To Reflect” model [21] adapted with the “To Link” step, will allow teachers to acquire a more holistic competence needed to overcome reluctance, enhance their self-efficacy, and allow them to seamlessly blend CT concepts into their future science classrooms.

3.1 Program Structure

The training is structured as a sequential, multi-step process that combines plugged activities, adaptive gamification, hands-on coding, and pedagogical reflection. Initially, the four pillars of CT are introduced, framed as problem-solving practices linked to scientific thinking to establish a clear connection to science (Content Knowledge) (CK), such as how taxonomists utilise pattern recognition or how chemists employ abstraction in molecular diagrams. Furthermore, the "To Play, To Think, To

Code, To Link" model is showcased (Pedagogical Knowledge) (PK) as a foundational framework to link CT and science education.

The next stage shifts focus to Technological Pedagogical Knowledge (TPK) by introducing the adaptive environment. Teachers initialise the custom Unity3D adaptive application, complete the Hexad questionnaire, and the system assigns them a specific player profile. They are familiar with the features of the environments, the tools they incorporate, and how their LA data will be applied to the learning process. Following this, the third step targets Technological Content Knowledge (TCK) through engagement with plugged CT activities for each concept and science linking. Teachers navigate the four modules within the application. As they complete specific game tasks, such as the party-planning activity in the "Abstraction" concept, they will immediately link the concept to science education through AI NPCs, for example, in the circuit symbol activity. Throughout this process, the instructor uses the LA dashboard to identify teachers who are struggling with the logic.

Moving forward, the teachers will be introduced to a block-based tool (TCK) and follow the "To Play, To Think, To Code, To Link." Teachers will transition from the structured, gamified application to a more open, creative environment, in this case, a custom block-based interface using a coding language similar to Scratch (To Play) (Figure 2). Here, teachers are introduced to already established programs with "bugs" that need fixing. Then they will engage in a guided discussion to decompose each application's logic and design a plan for its construction (to think). Following that, they will use the environment to test their ideas and create a working program (to code). Finally, through discussions with the AI NPCs, the students connect their task to scientific inquiry (to Link) (TPACK). Teachers are guided to recognise that their previous coding activities are directly linked to scientific experimental design, i.e., hypothesis formulation, experimentation, analysis, and revision. At all stages, the instructor monitors students' learning using the LA and intervenes as necessary.

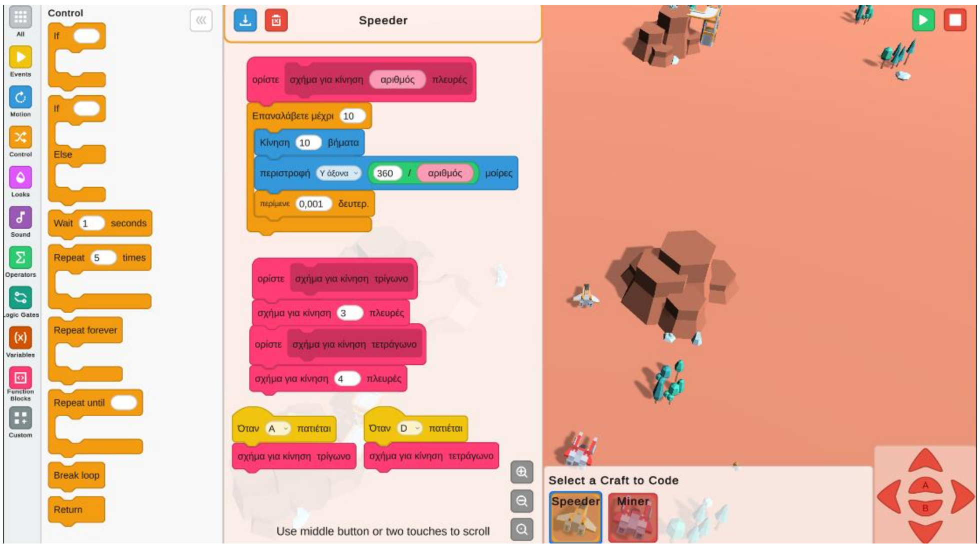

Fig. 2. Custom Block-based interface that uses coding similar to Scratch

Following that, the teachers exit the application and conduct group discussions in order to prepare for the transfer of their newly acquired skills to practical application (TPACK). Then they are tasked with utilizing these new concepts to design a science lesson. This step ensures that computational thinking is understood as a cognitive tool for scientific inquiry, rather than merely a coding skill.

4. Conclusion

The integration of CT into preschool and primary science education is directly linked with teachers' readiness, self-efficacy, and confidence. This study addressed this critical gap in teacher education by proposing a novel adaptive gamification application enhanced with an LA dashboard and a professional development framework grounded in the TPACK model. By moving beyond traditional "one-size-fits-all" training methods, the proposed methodology tailors the learning experience to individual motivational profiles, leveraging self-determination theory through the Hexad model, AI NPCs, and students' LA data. This personalised approach fosters engagement and reduces cognitive load, enabling pre-service teachers to master essential concepts of CT within a supportive digital

ecosystem. Additionally, this pedagogical structure is fundamentally supported by the TPACK framework, which has shown to significantly enhance teachers' knowledge, motivation, and self-efficacy, especially when combined with adaptive gamification [17, 25]. Moreover, although the PD program is suitable for both in-service and pre-service teachers, the focus here is on pre-service teachers, who are more likely to be flexible and receptive to new pedagogies.
In the teacher-instructor role, the strategic integration of real-time LA enables them to serve as facilitators, monitor trainee progress, and provide precise, data-informed interventions. This ensures that the technology enables adaptive learning while keeping the instructor central, guiding students through the learning process and pedagogy, as in the "To Play, To Think, To Code, To Link" pedagogy. Consequently, the program does not merely teach CT skills, but it explicitly aims to bridge the gap between computational logic and scientific inquiry, equipping teachers to apply these tools in experimental design and hypothesis testing.
Ultimately, this study offers a comprehensive blueprint for modernising science teacher education. By combining adaptive technologies with robust pedagogical strategies, the program aims to cultivate a generation of educators who are not only digitally literate but also capable of transforming science classrooms into dynamic, problem-solving environments. As the adaptive gamification environment is still in the alpha stage, future research will focus on empirically validating this framework after finalising the application and LA dashboard to assess its impact on teachers' self-efficacy and readiness to design lesson plans to teach science concepts based on CT.

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