An AI-Powered Learning Companion for Adaptive and Personalized STEM Education

Nikolaos Antonios Grammatikos[1], Evangelia Anagnostopoulou[1], Dimitris Apostolou[2] and Gregoris Mentzas[1]

[1] Information Management Unit, Institute of Communication and Computer Systems, National Technical University of Athens, Athens, Greece
[2] Department of Informatics, University of Piraeus, Piraeus, Greece

Abstract. We introduce an AI learning companion designed to enhance STEM education by providing personalized, adaptive learning experiences. The companion dynamically adjusts the difficulty of experimental activities in online STEM labs and delivers targeted feedback based on real-time student performance, ensuring a more efficient learning process. Teachers can use the companion's authoring tool to create tailored educational scenarios that cater to students at various performance levels. This work emphasizes a student-centered approach, supporting critical thinking and problem-solving skills.

Keywords: AI agent, learning companion, STEM learning, education

1 Introduction

The use of AI-powered conversational agents in education has gained momentum over the past few years, providing personalized learning environments and enhancing student engagement. These systems, such as chatbots, facilitate real-time interactions, offering students instant feedback, answering questions, and even tutoring them in specific subjects.

Digital courses refer to educational programs that are predominantly delivered through digital platforms, leveraging online technologies and multimedia resources. Students typically engage with the course content asynchronously, allowing them to interact with the material according to their individual schedules and learning preferences. Platforms such as WhoTeach [1] support educators by offering tools and resources to design and develop their own customized digital courses, thereby enhancing instructional delivery and promoting active learning through technological integration.

In this paper, we present the development of an AI learning companion and a supporting platform for educational scenario creation. The research objectives of our work are to provide personalized support to students as they engage with educational scenarios developed by their teachers. To achieve our objective, we propose an approach for analyzing student performance data, delivering targeted feedback and adjusting the difficulty of tasks dynamically, based on the students' performance within their learning path. This approach aims to personalize the learning process by ensuring that students are both appropriately challenged and supported, fostering a deeper understanding of the material and enhancing overall learning outcomes.

The structure of this paper is as follows: Section 2 explores the use of AI digital assistants in education, providing a foundation for the current work. In Section 3, we present the design and development of our AI learning companion, along with the platform that enables educators to create customized educational scenarios. Section 4 offers a discussion on the system's implementation and outlines future directions for both the learning companion and the platform. Finally, Section 5 concludes the paper with final remarks and considerations.

2 AI Digital Assistants in Education

In the domain of education, AI is emerging as a pivotal force, with tools like ChatGPT driving transformative changes across various domains, from assessment design to language learning [2]. AI digital assistants offer personalized support to both students and teachers in various educational environments [3]. These assistants can help students grasp new concepts, complete assignments, and get answers to their questions through conversational interfaces, whether text-based or voice-activated.

This paper specifically focuses on dialogue-based systems for student learning, where learners engage with educational content through natural language conversations but also the learning environment where educators can create educational scenarios for their students or gather insights from those scenarios. In the following, we describe the digital assistants identified in our research.

AutoTutor is an intelligent tutoring system that engages students in conversation, helping them learn by simulating human tutoring interactions. The system adapts to student performance and misconceptions to provide individualized instruction [4]. The Curriculum-Driven EduBot [5] is an AI-powered chatbot designed for conversational practice based on specific curricula. Unlike generic chatbots, it focuses on predetermined topics and uses vocabulary directly from textbooks to match learners' proficiency levels.

An LLM based assistant named CodeAid [6] provides various functionalities, allowing students to ask general programming questions, seek help with code they have written, request explanations, troubleshoot errors, or receive guidance in writing new code. Georgia University developed Jill Watson [7], a chatbot powered by IBM's Watson Platform, to manage forum posts in a programming course. During its 2016 pilot, the chatbot effectively answered student queries and provided feedback. Jill Watson was later refined and integrated alongside human teaching assistants, with students unable to distinguish between the AI and human support.

Ani [8], a chatbot developed by Duolingo, is specifically designed to help users improve their conversational skills in a foreign language. Using natural language processing, Ani understands and responds to user inputs, offering personalized feedback on grammar, pronunciation, and vocabulary usage. It also suggests conversation topics tailored to the learner's interests and language level. HuBERT (Hidden Unit BERT) [9]

[10] is a self-supervised learning model designed to process continuous speech inputs, building on the BERT model's framework, automating the process of providing feedback to educators.

3 Design and development of the learning companion

3.1 Overview

This research focuses on developing an AI-powered learning companion designed to facilitate STEM education by guiding students through experimental activities in online STEM labs. Figure 1 illustrates the conceptual design of our platform, which integrates tools such as PhET simulations and remote experiments to engage students in interactive and immersive learning. Educators use the authoring tool to create customized educational scenarios, which the AI learning companion leverages to adaptively guide students through these scenarios. Based on real-time student performance, the companion categorizes learners into three groups: high performers, moderate performers, and low performers. Each group is provided with a tailored learning path within the same scenario, adjusting the level of challenge and support accordingly. This adaptive approach ensures that all students—regardless of their initial performance level—receive personalized learning experiences that align with their abilities, promoting more effective and targeted educational outcomes.

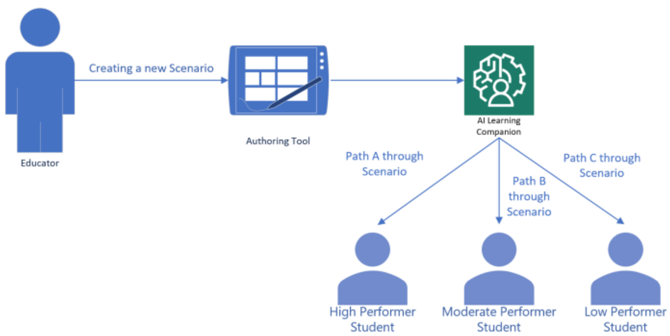

Fig. 1. Conceptual Design of Teacher-Platform and AI Learning Companion-Student Interactions

Rather than adhering to a traditional instructionist model, the assistant promotes continuous, adaptive learning based on each student's interests and evolving goals. It empowers students to take ownership of their learning by deciding what to study, how to approach challenges, and where to focus their efforts. By guiding them through customized learning paths, the assistant not only helps students achieve short-term learning objectives but also encourages them to reflect on their long-term educational aspirations.

3.2 Technical implementation

The system's technical foundation, built using Django, PostgreSQL, and the Rasa framework, ensures scalable and robust deployment, with future developments focusing on integrating reinforcement learning to further refine the assistant's ability to adapt to student needs. The learning companion has been developed using Rasa open-source framework for building conversational AI using machine learning techniques. Rasa is composed of two main components: Rasa NLU (Natural Language Understanding) and Rasa Core.

Rasa NLU is responsible for understanding user input by handling natural language processing (NLP) tasks. It includes:

- Intent Recognition: Rasa NLU identifies the user’s intent by classifying the input into predefined categories like "greeting," "question," or "action request."
- Entity Extraction: This part of Rasa identifies and extracts key entities from the text (e.g., dates, names, or locations). Rasa NLU uses pre-trained machine learning models, and it also allows custom pipelines where developers can choose the specific language models and libraries suited to their use case.

Rasa Core handles dialogue management, which involves deciding how the assistant should respond based on the user’s input and conversation history. Its architecture is built on Recurrent Neural Networks (RNNs) with an attention mechanism that enables it to learn from the context of previous interactions and predict appropriate responses.

- Stories: In Rasa, stories are training examples that define how the assistant should respond to a series of user inputs. They help the assistant learn to handle complex and multi-turn conversations.
- Policies: Rasa Core uses policies that define how the assistant behaves. For example, the Memorization Policy recalls exactly what the assistant should say in previously encountered situations, while the TED Policy uses machine learning to generalize responses in unseen conversations.

3.3 Practical Applications of Educational Scenarios

The learning companion offers a tailored learning experience for students by dynamically adapting content based on individual performance and engagement. For example, a student engaging with a physics experiment, such as the photoelectric effect simulation, may receive questions personalized to their level of understanding. As shown in Figure 2, the AI assistant interacts with students as they perform the PhET simulation within the platform, providing real-time feedback and analyzing their responses. Using this analysis, the assistant categorizes students into high, moderate, or low performers, ensuring that each learner follows a path aligned with their current capabilities.

Based on the classification system outlined, the AI learning companion can accurately categorize students into high, moderate, and low performers within an educational scenario. This classification is determined using specific performance ranges. Students with a performance score between 1.00 and 1.49 are categorized as low performers, those with a score between 1.50 and 2.49 are identified as moderate performers, and students scoring between 2.50 and 3.00 are classified as high performers. Each category corresponds to differentiated learning paths, tailored to meet the specific needs and abilities of the students, within the same scenario. These performance thresholds align with the values attributed to different problem-solving processes as defined by the OECD [11], ensuring that the companion's adaptive learning strategies follow recognized educational standards.

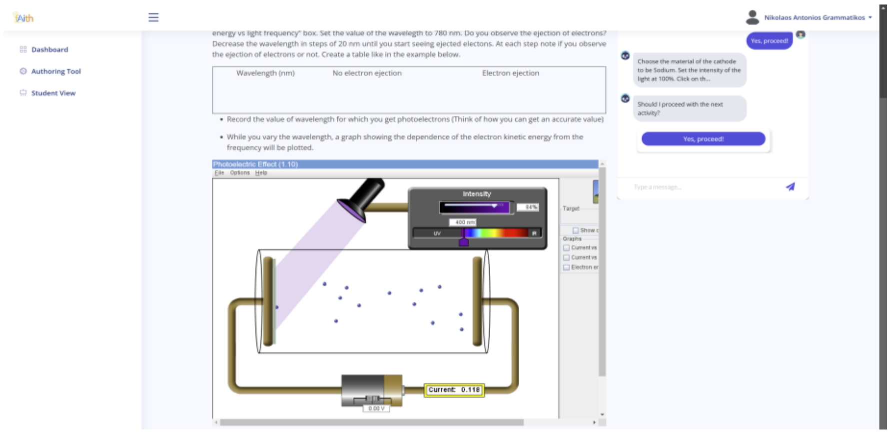

Fig. 2. Phet Experiment during Photoelectric Effect Scenario

In addition to the photoelectric effect simulation, the platform offers a wide range of other physics experiments, each accompanied by interactive PhET simulations. These include well-known experiments such as Newton's Laws of Motion, the Pendulum, and Galileo's work on gravitational waves. By incorporating these diverse simulations, the platform provides students with opportunities to engage deeply with key scientific concepts, enhancing their understanding through hands-on experimentation and real-time feedback from the AI learning companion.

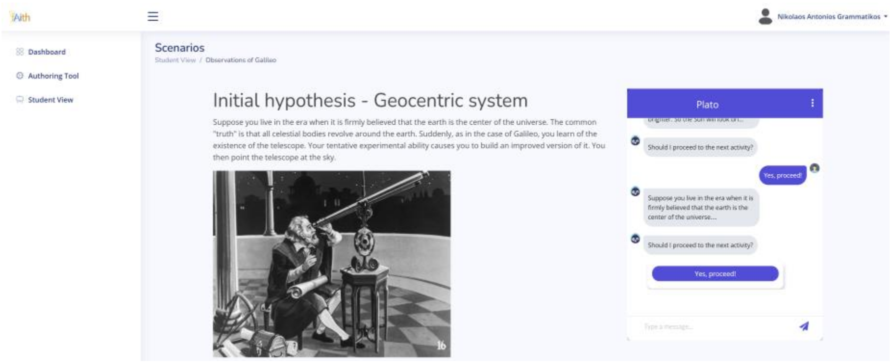

Fig. 3. Explanation for Geocentric system during Observations of Galileo Scenario

If the student struggles with a concept, the companion provides additional explanations, hints, or alternative questions to reinforce understanding. For high performers, the system may increase the difficulty of questions or introduce more complex experiments to offer greater challenges. The companion continuously tracks the student's engagement, feedback, and progress to adjust the learning pathway, ensuring that each student receives a personalized learning experience tailored to their capabilities. As illustrated in Figure 3, the student receives a detailed explanation based on their responses to previous questions, providing targeted feedback to help bridge any gaps in understanding.

Additionally, students can engage with various content formats, based on their preferences. For instance, a student showing better engagement with video-based content might be presented with more video tutorials, while another may be guided through interactive simulations or text-based explanations, depending on what maximizes their learning efficiency.

4 Discussion and Future Work

We plan to conduct several pilot studies with teachers and students from various European schools. Using the platform's dashboard, we will monitor and analyze student reactions to gather insights and refine the system. Looking ahead, we aim to introduce technical enhancements, including the integration of trustworthy AI to streamline the creation of educational scenarios with enriched content. By incorporating reinforcement learning, the assistant will be able to adapt to student feedback, engagement, and performance, continuously improving its intelligence and offering greater value to both students and educators. As shown in Figure 4, the Sankey diagram illustrates the progression of high, moderate, and low performers through various stages of learning activities, highlighting the system's ability to adaptively support students according to their performance.

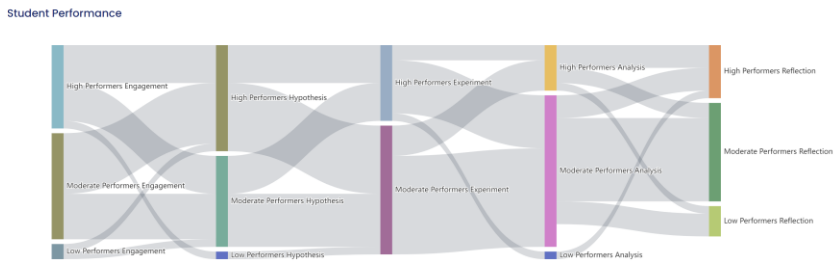

Fig. 4. Sankey diagram showing the alterations between student performance

Additionally, we aim to integrate generative AI as an assistive tool for educators in the scenario creation process. This will enhance the scope and engagement of educational content by enabling teachers to develop richer and more interactive scenarios for their students. Importantly, this approach is designed to augment, rather than replace, the essential human input, ensuring that the teacher's expertise and oversight remain central to the educational experience while leveraging AI to enhance content generation and engagement.

To ensure our AI-powered educational system is trustworthy, we plan to implement several key measures focused on accuracy, and human oversight, following the European Commission's Ethics Guidelines for trustworthy AI [12]. One significant approach is to incorporate expert reviews and guided content customization, allowing educators to refine AI-generated learning materials and ensure alignment with educational standards. Periodic evaluations by experts further enhance the quality of the AI's outputs, ensuring the content remains pedagogically sound. Additionally, automated hint generation is governed by robust safety protocols to ensure that students receive accurate guidance without the risk of inappropriate or misleading content.

Fairness and personalization are also prioritized through AI-driven student groupings and content adaptation. To avoid bias, group formation processes will be regularly analyzed, and content delivery will be tailored to individual learning preferences based on engagement metrics. By continuously monitoring performance and engagement, the system will dynamically adjust learning pathways, ensuring that students remain engaged and that their educational experiences are optimized. These measures collectively ensure that the AI system promotes equitable, personalized learning while maintaining high ethical and educational standards.

5 Conclusion

The learning companion and the platform presented in this paper was developed to support students engaging in STEM educational scenarios. The companion draws on expert knowledge and real-time student performance data to deliver personalized, adaptive learning experiences. By dynamically adjusting the difficulty of tasks and offering individualized feedback, the assistant ensures that students can progress efficiently, strengthening their critical thinking and problem-solving skills while mastering complex scientific concepts. The companion has demonstrated its ability to accurately discern user intentions and generate relevant responses, resulting in a seamless and effective learning experience. The findings of this study suggest that the Rasa technology holds promise as a valuable platform for facilitating interaction and communication in a variety of educational settings.

The ongoing work outlined in this paper establishes a technical infrastructure aimed at fostering innovation, technological fluency, and creative methodologies to effectively utilize advanced conversational applications in educational settings. By utilizing AI to enhance learning processes and address localized educational challenges, we aim to demonstrate the potential of AI in improving student cognition and learning outcomes, rather than merely replacing human capabilities. Furthermore, our goal is to show how AI-driven conversational technologies can reflect and adapt to the evolving educational needs of students. The proposed educational approach can make a meaningful contribution to empower students to solve complex problems.

Acknowledgments. The work presented here is funded by the European Union's Horizon FAITH project (Fostering Artificial Intelligence Trust for Humans towards the optimization of trustworthiness through large-scale pilots in critical domains), Grant agreement No 101135932. The work presented here reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

References

1. https://www.whoteach.it/
2. Sukhpal Singh Gill, Minxian Xu, Panos Patros, Huaming Wu, Rupinder Kaur, Kamalpreet Kaur, Stephanie Fuller, Manmeet Singh, Priyansh Arora, Ajith Kumar Parlikad, Vlado Stankovski, Ajith Abraham, Soumya K. Ghosh, Hanan Lutfiyya, Salil S. Kanhere, Rami Bahsoon, Omer Rana, Schahram Dustdar, Rizos Sakellariou, Steve Uhlig, Rajkumar Buyya, Transformative effects of ChatGPT on modern education: Emerging Era of AI Chatbots, Internet of Things and Cyber-Physical Systems, Volume 4, 2024, Pages 19-23, ISSN 2667-3452, https://doi.org/10.1016/j.iotcps.2023.06.002.
3. U. Maier, C. Klotz Personalized feedback in digital learning environments: Classification framework and literature review, Computers and Education: Artificial Intelligence, 3 (2022), Article 100080, 10.1016/j.caeai.2022.100080
4. Graesser, A. C., & McNamara, D. S. (2010). AutoTutor and Coh-Metrix: Facilitating Learning through Natural Language Conversations, Discourse, and Situation Models. Topics in Cognitive Science, 2(2), 104-122.
5. Li, Y., Qu, S., Shen, J., Min, S., & Yu, Z. (2023). Curriculum-Driven Edubot: A Framework for Developing Language Learning Chatbots Through Synthesizing Conversational Data. arXiv preprint arXiv:2309.16804.
6. Majeed Kazemitabaar, Runlong Ye, Xiaoning Wang, Austin Zachary Henley, Paul Denny, Michelle Craig, and Tovi Grossman. 2024. CodeAid: Evaluating a Classroom Deployment of an LLM-based Programming Assistant that Balances Student and Educator Needs. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 650, 1–20. https://doi.org/10.1145/3613904.3642773
7. G. Ashok, C. Brian, K. Mithun, S. Shanu, S. Abhinaya, and W. Bryan, Using Watson for enhancing human-computer co-creativity. AAAI Symp., 2015, pp. 22–29.
8. G. Garcia Brustenga, M. Fuertes-Alpiste, and N. Molas-Castells, Briefing paper: los chatbots en educación, Universitat Oberta de Catalunya, eLearn Center, Barcelona, 2018. https://doi.org/10.7238/elc.chatbots.2018
9. Mora, A. M., Guillén, A., Barranco, F., Castillo, P. A., & Merelo, J. J. (2021, July). Studying how to apply chatbots technology in higher-education: first results and future strategies. In Learning and Collaboration Technologies: Games and Virtual Environments for Learning: 8th International Conference, LCT 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings, Part II(pp. 185-198). Cham: Springer International Publishing.
10. Wei-Ning Hsu, Benjamin Bolte, Yao-Hung Hubert Tsai, Kushal Lakhotia, Ruslan Salakhutdinov, Abdelrahman Mohamed (2021, June). HuBERT: Self-Supervised Speech Representation Learning by Masked Prediction of Hidden Units, https://doi.org/10.48550/arXiv.2106.07447
11. OECD (2017), "PISA 2015 collaborative problem-solving framework", in PISA 2015 Assessment and Analytical Framework: Science, Reading, Mathematic, Financial Literacy and Collaborative Problem Solving, OECD Publishing, Paris, https://doi.org/10.1787/9789264281820-8-en.
12. European Commission and Directorate-General for Communications Networks, Content and Technology, Ethics guidelines for trustworthy AI, Publications Office of the European Union (2019), https://digital-strategy.ec.europa.eu/en/library/ethics-guidelines-trustworthy-ai