AI-Infused Collaborative Inquiry in Upper Elementary School: A Game-Based Learning Approach

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Abstract

Artificial intelligence has emerged as a technology that is profoundly reshaping society and enabling rapid improvements in science, engineering, and mathematics, as well as information technology itself. This has generated increased demand for fostering an AI-literate populace as well as a growing recognition of the importance of promoting K-12 students' awareness and interest in AI. Although efforts are beginning to incorporate AI learning within K-12 education, there is little research exploring how to introduce students to AI and how to support teachers to integrate AI learning experiences in their classrooms. This is especially true at the elementary school level. A particularly promising approach for providing effective and engaging AI learning experiences for elementary students is game-based learning. In this paper, we explore how to introduce AI-infused collaborative inquiry learning into upper elementary school (student ages 8 to 11) using game-based learning. To ground the work in the realities of elementary school classrooms, we present insights from interviews with elementary school teachers to understand how best to support them in integrating AI into their classrooms. We then present the design of PRIMARYAI, a game-based learning environment that supports rich problem-based learning activities within upper elementary classrooms centered on AI applied toward solving life-science problems. Finally, we discuss some of the challenges we face in bringing AI-infused collaborative inquiry learning to upper elementary students.

Introduction

Artificial intelligence (AI) has emerged as a foundational technology that is fundamentally reshaping the workplace of the future (McKinsey Global Institute, 2017; West, 2018). With rapid developments in a wide array of capabilities ranging from automated reasoning, computer vision, robotics, and machine learning, AI is becoming a critical tool for enabling improvements in science, technology, engineering, and mathematics (Manyika 2017). This has generated a vital need to develop a deep understanding of how to best introduce K-12 students to AI (Touretzky et al. 2019), and how to best support K-12 teachers in integrating AI learning experiences into their classrooms.

Recognizing the importance of fostering K-12 students' awareness and interest in AI, emerging efforts are underway to incorporate AI within K-12 education (Ali et al. 2019; Touretzky et al. 2019), as well as to establish guidelines for K-12 AI education (AAAI 2018). However, there has been limited research examining AI learning and teaching at the elementary level. Because early learning experiences can significantly affect future academic and career trajectories, it is essential to create engaging AI learning experiences for elementary school students.

Game-based learning is a powerful tool for creating effective and engaging learning experiences through immersive problem solving (Wouters 2013; McLaren et al. 2017). Game-based learning environments, with the potential to motivate students with inviting settings, expressive characters, and compelling virtual worlds, are being used to create engaging, effective computer science (CS) and AI learning experiences in K-12 classrooms (Buffum 2016; Wang and Johnson 2019), including fostering computational thinking in the elementary grades (Rowe et al. 2017). Well-designed game-based learning environments enable students to develop problem-solving skills, communicate and collaborate with other students, and actively participate in rich virtual contexts (Gee 2003; Salen 2007; Shaffer 2006). Similarly, inquiry-based learning approaches for CS have yielded encouraging results that demonstrate improved student engagement (Hoffman et al. 2019), student achievement

(Hoffman et al. 2019; Chen and Yang 2018), and student attitudes towards CS (Hoffman et al. 2019; Pollock et al. 2017). Inquiry-based learning approaches for CS are also being explored at the elementary level. Given the potential to support student engagement and achievement, leveraging inquiry-based strategies, such as problem-based learning, along with game-based learning offer significant potential for promoting AI education in elementary school classrooms.

Recognizing the need to provide all students with AI learning opportunities, we are investigating PrimaryAI, a game-based learning environment featuring AI-infused inquiry learning that will enable students to gain experience with AI applied toward solving life-science problems. In this paper, we present initial work on the design of PrimaryAI, which is being used to explore two key research questions focused on introducing AI education into upper elementary classrooms.

1. *How can we create engaging learning experiences that integrate artificial intelligence and life science for upper elementary students with game-based learning?*

2. *How can we support upper elementary school teachers with integrating artificial intelligence and life science into their classrooms?*

This paper is structured as follows. First, we provide background on K-12 AI education as well as research we are drawing on to create the PrimaryAI learning environment: game-based learning and problem-based learning. Next, we introduce the design of our game-based learning environment for AI-infused collaborative inquiry learning in elementary school. We present interviews with elementary school teachers to better understand how to support them in introducing AI into their classrooms. We also present our approach to combining techniques from game-based learning and problem-based learning to create AI-infused collaborative learning experiences for students. Finally, we present findings, concluding remarks, and directions for future work.

Related Work

Integrating game-based learning and problem-based learning offers significant promise for creating engaging and effective learning experiences. However, limited work has investigated AI-infused learning experiences for upper elementary school students. In this section, we survey prior work o[1]n AI education for K-12, game-based learning, and problem-based learning.

K-12 AI Education

Emerging efforts are beginning to explore how to incorporate AI more intentionally at the K-12 levels. For example, the Association for the Advancement of Artificial Intelligence (AAAI) and the Computer Science Teachers Association (CSTA) formed a working group in 2018 to begin identifying the important constructs of AI for K-12 students to learn. Touretzky et al. (2019) consider how AI might be introduced to K-12 students, and Webb and colleagues (Webb et al. 2017) suggest that learners need to understand to truly evaluate AI by "understanding what the nature of a computer program is (does it 'think'?), what kind of knowledge base (data) it could collect and store, its access to our digital infrastructure, the way that humans would interact with it, and the philosophical concerns about human rights and what intelligence is" (p. 461). Similar efforts for K-12 AI education are underway around the globe (Touretzky et al. 2019).

Efforts are also underway to develop tools and curricula to support AI education within K-12 classrooms. For example, Google's Teachable Machine[1] is a web-based tool that enables students to create machine learning models to recognize images, poses, and sounds. Cognimates allows students to engage in programming activities that include training their own AI models to perform speech recognition, sentiment analysis, and image classification (Druga 2018). Machine Learning for Kids helps students build programs using Scratch that leverage AI models powered by IBM Watson (Lane 2019). In addition, companies such as ReadyAI[2] are creating pre-configured toolkits, such as AI-in-a-Box, that include both hardware and software to support AI education for K-12 students. Work is also underway to develop modules to support students in learning about ethical issues in AI (Yeh et al. 2019), exploring machine learning concepts in elementary school (Lin et al. 2020), and teaching machine learning and natural language processing to high school students (Norouzi et al. 2020).

Game-Based Learning

The educational potential of games has garnered significant attention that has been directed toward appropriating the best features of games and transferring them to educational settings (Gibson et al. 2007). For example, several commercial games that focus on entertainment (e.g., Civilization, SimCity, and Spore) have loosely incorporated educational themes into gameplay, includ[2]ing history, urban planning, and evolution. Game-based learning environments create engaging, situated learning experiences for students that prioritize academic subjects, pedagogy, and problem solving. Efforts to systematically review the game-based learning literature have found that digital games are often more effective than traditional instructional methods in terms of

[1]https://experiments.withgoogle.com/ai/teachable-machine/
[2]https://www.readyai.org/

enhancing learning outcomes (Wouters et al. 2013; Clark et al. 2016). By encouraging students to actively participate in situated problem-solving activities, game-based learning environments promote deep, meaningful student learning.

Researchers have investigated game-based learning environments for a variety of educational domains, including anti-bullying (Aylett et al. 2005), science learning (Ketelhut et al. 2007; Rowe et al. 2011), interactive health-education (Marsella 2003), graphics design (Cutumisu 2018), mathematics (Mogessie et al. 2020), and computational thinking (Min et al. 2017; Zhao and Shute 2019). Efforts are now underway to leverage game-based learning to connect AI concepts, such as search, reasoning, and machine learning to high school math (Wang and Johnson 2019). A broad range of computational frameworks have been investigated that can be used to enhance student interactions during game-based learning, ranging from predictive student models of engagement from gameplay data (Sawyer et al. 2018) to better understanding how players engage and disengage while playing games (Hadiji et al. 2014; Bertens et al. 2017), as well as student-adaptive experience managers for personalized gameplay (Kantharaju et al. 2018; Yu and Riedl 2015) and assessing student learning without interfering with gameplay (Min et al. 2017; Shute and Sun 2019). Through these games and frameworks effective and engaging learning experiences are being created for a broad range of subject matters and target student populations.

Problem-Based Learning

Problem-based learning is an effective student-centered approach to collaborative learning that supports small groups of students learning through the investigation of complex, ill-defined problems (Barrows 1986; Hmelo-Silver et al. 2004). Problem-based learning holds that students need to be active learners, and learning occurs as knowledge is shared and negotiated among group members (Hmelo-Silver et al. 2018). Teachers serve as facilitators during problem-based learning to support student learning, and their interventions diminish as students progressively take on responsibility for their own learning processes (Dolmans and Schmidt 2006; Hoffman et al. 2019). Problem-based learning was originally formalized as an instructional model for medical schools in the 1960s; however, recent years have seen increasing interest in applying it to K-12 education (McConnell et al. 2016). The significant opportunity provided by the rich, situated problem contexts of game-based learning to support problem-based learning is starting to be investigated (Mott et al. 2019), and using game-based learning to introduce AI education in elementary classrooms is an unexplored area.

AI-Infused Inquiry Learning

PRIMARYAI is a game-based learning environment for upper elementary students that provides AI learning experiences through AI-infused life-science problem solving. The game is being developed using the Unity® game engine, a cross-platform game development environment that supports WebGL deployments as well as standalone application deployments. PRIMARYAI's problem-based learning scenarios take place within an expansive storyworld, which is being specifically designed to support AI-infused upper-elementary science education. This integration of AI into science instruction offers the benefit of engaging diverse groups of learners who might otherwise not elect to explore AI learning opportunities.

Teacher Insights to Inform Design

To ensure that PRIMARYAI meets the needs of teachers and students in bringing AI learning experiences to upper elementary classrooms, a participatory co-design process is used, in which teachers are actively engaged in the instructional design process (DiSalvo et al. 2017). By having teachers participate in the design of problem-solving scenarios pertaining to AI for young learners, they help to ensure that PRIMARYAI addresses their needs, the needs of their students, and works within the constraints of traditional schools and classrooms.

Using a co-design approach adapted from Könings, Brand-Gruwel, and Merrienboer (Könings et al. 2010), we are working with teachers to (1) brainstorm positive and negative experiences regarding computer science, AI, life science, and problem-based learning, (2) describe and discuss the most important positive and negative aspects of the AI-infused learning experiences, and (3) discuss possible ideas for improving the negative points that emerge. As part of our co-design activities, three teacher interviews were conducted to gather baseline data around their current knowledge and comfort levels with computer science, AI, life science, and problem-based learning. The interviews also served as an opportunity to begin developing relationships and onboarding the teachers into the co-design process.

Participants and Procedure: Participants were recruited from local STEM teacher professional development programs in the Midwestern United States that focus on improving STEM workforce development. The teachers volunteered to participate in the co-design activities. All three teachers have been teaching for at least 10 years at the elementary school level and currently serve as coaches for their respective school STEM programs. Semi-structured interviews were conducted in person during the school day. The interviews were transcribed and analyzed using the constant comparative analysis method (Glaser 1965).

Qualitative Analysis: While reviewing the interviews in their entirety, we labelled themes that developed based on the teachers' responses to the open-ended questions. This includes their perceptions regarding their attitudes, beliefs, and efficacy on teaching computer science, AI, life science, and problem-based learning topics. We separated the data into two key themes: (1) content knowledge and pedagogical efficacy, and (2) supports that the teachers feel they need to better teach these topics. The following excerpts were taken from the conversation during the interviews.

Content Knowledge and Pedagogical Efficacy: The participants were asked about their previous experience with computer science and coding.

"I never heard of coding until I took professional development a few years ago. Then I had training in Code.org, Scratch, and Tinker." – Participant A.

"Although I attended Code.org professional development and have implemented programming lessons with Scratch and Code.org., I have not integrated these lessons into other subjects." – Participant B.

"I am at a pilot school with a full time computer science teacher, so I haven't received any formal computer science professional development training through the school." – Participant C.

The participants indicated that although they had some training, they were novices and had limited experiences in teaching CS in their classrooms. The participants were also asked how important it is to teach computer science at the elementary level.

"Very important, but it is very difficult to tie what the students are learning to real-world applications and their potential careers. Eventually, all students, however, will need skills in computer science." – Participant A.

"Extremely important because the more we hear about what the jobs are going to be like 20 years from now, I think it's imperative that they have those skills and I feel that if they are not introduced to them early, then I am doing a disservice to my kids. That's what I want for my own children, to be prepared for their future." – Participant B.

"Incredibly important because it is impacting everything. It will help students break out of the cycle of poverty by affording them the opportunity to have good jobs." – Participant C.

The participants described that CS was important for students and their futures. They recognized that CS would be a fundamental part of their students' future lives. The participants were also asked about their concerns teaching computer science.

"My concern is 'do I have the knowledge to teach it?' I am good at figuring things out as I work with the students. I am willing to try things, even if I fail. I can say to the kids, 'I really don't know how to do that, but we can figure it out (together)'." – Participant A.

"Other than the fact that I don't know a lot – so I am nervous about teaching things I don't know… when it doesn't go like you expect it to, it is a little stressful… which is why I often invite people in who do know. I use a lot of STEM professional volunteer experts in the classroom." – Participant B.

"My concern is that I do not have enough time. It wasn't in the standards so it wasn't on the radar and now it's in the standards." – Participant C.

The participants described that although they did think CS was important, they were apprehensive about their knowledge and abilities to teach CS. However, they had each identified strategies that they could use to deal with their lack of CS knowledge. The participants were also asked how important it is to teach artificial intelligence at the elementary level.

"I have no knowledge about it… [but it] is where a lot of things are headed." – Participant A.

"I don't know a whole lot, I do feel that it is going to be a wave of the future – and highly important. And it's connected to computer science, so they (students) need to learn it, as much as they can." – Participant B.

"Very important that we teach students to be aware of how AI is being used in our society and the consequences of using AI." – Participant C.

The participants shared that although they were unfamiliar with AI, they recognized the importance of knowing about AI for the future. They were asked about their concerns teaching artificial intelligence, but because they were not clear on what AI was, they were not as apprehensive as computer science.

"I really wouldn't have any concerns because I don't know what it entails." – Participant A.

"Since I don't know very much about it, I would say none at this time." – Participant B.

"I am going to need a lot of professional development, and ideas, and background." – Participant C.

Supports Needed: The participants were asked about what types of support (tools or information, for example) do you need to help you be successful in teaching computer science and artificial intelligence to your classes? If you could ask for anything?

"I have enough hardware and software. More professional development will be beneficial. With computer science, I get frustrated at the beginning of week-long workshops, but by the end of the week, I feel more comfortable, and that's good. It is important that workshops aren't just one-day workshops." – Participant A.

"More professional development. I have enough resources." – Participant B.

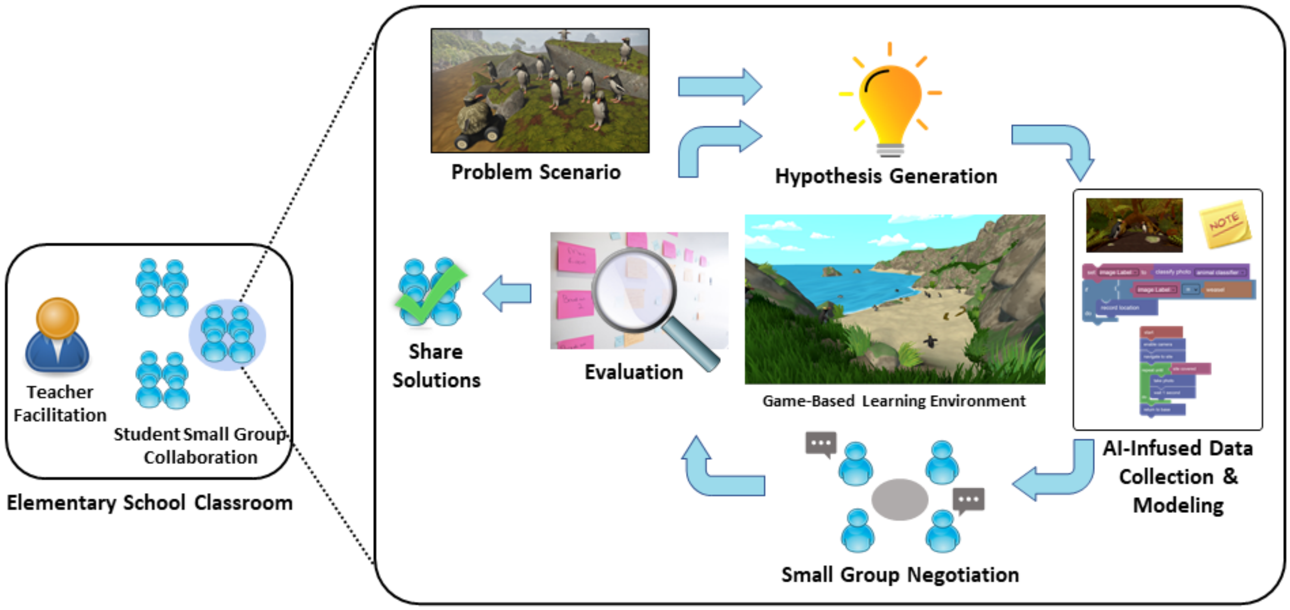

Figure 1: AI-Infused Game-Based Learning

"More time and better curricula... I am looking for scripted curricula... that is also open-ended for students." – Participant C.

The participating teachers' responses reflect their understanding of the importance of teaching AI juxtaposed by their anxiety pertaining to their lack of content knowledge and ability to teach the subject. The results suggest that providing more immersive and comprehensive professional development focused on AI content knowledge may help support teachers in adopting PRIMARYAI. In addition, PRIMARYAI will need to incorporate grade level appropriate activities for students.

AI-Infused Game-Based Learning Design

With a focus on the life sciences in general and ecology in particular, PRIMARYAI is being designed to enable students to learn about AI as they address science problems with AI tools in the context of inquiry-based science adventures. The learning environment's curricular content is driven by the Next Generation Science Standards (NGSS Lead States 2013) with a focus on disciplinary core ideas in the life sciences as well as concepts and practices from the K-12 Computer Science Framework (K-12 Computer Science Framework 2016) oriented towards age-appropriate AI concepts. PRIMARYAI is designed to support small groups of students through problem-based learning cycles as they collaboratively engage with immersive life-science problem scenarios while gaining hands-on experience through exploration of AI-based methods (Figure 1).

In the PRIMARYAI game-based learning environment, students will play the role of an ecologist who is investigating the recent declining population of yellow-eyed penguins on New Zealand's South Island. After a brief period of exploration, students learn that their overarching task is to investigate the driving question: *What is causing the recent decline in the native population of yellow-eyed penguins on the island?* After generating initial hypotheses and taking notes about what they already know and what they need to learn, the students are prompted by an in-game virtual character to begin gathering data about the local penguin population. However, the penguin colony is difficult to access on-foot, and further, the penguins are notoriously shy around humans. Therefore, the students utilize simulated semi-autonomous robots, disguised as baby penguins, to remotely collect images, audio recordings, and other data to serve as evidence for explaining recent changes to the penguin population and surrounding habitat. Using a block-based programming interface that is embedded within PRIMARYAI, the students complete a series of in-game "quests" in which they formulate internal agent programs for planning, reasoning, and decision making to be carried out by the robots. As the students progress through the quests, they are prompted by their teacher to work together to discuss, negotiate, and evaluate their hypotheses based on their latest findings in their groups.

The students continue their explorations in PRIMARYAI over the course of several class periods, completing a series of AI-centric problem scenarios while sharing their solutions with the class. By engaging with programs and abstractions that are age-appropriate, students gain hands-on experience with AI-based methods applied toward solving immersive life-science problems. In this manner, PRIMARYAI integrates problem-based learning, AI, and ecological science concepts for upper elementary science education.

AI-Infused Block-Based Programming Design

PRIMARYAI leverages block-based programming to support students' problem solving. Block-based programming is an effective approach for teaching computational thinking skills to novice learners (Bau et al. 2017). By reducing cognitive load and reducing the ability to produce syntax errors, block-based programming environments create engaging learning experiences to introduce students to programming. Recent work to support AI education for K-12 students is using block-based programming (Druga 2018; Lane 2017). Building on a toolkit developed in our lab for integrating block-based programming into game-based learning environments (PRIMARYAI), we are seamlessly integrating block-based programming into problem-solving scenarios in PRIMARYAI. Using the Blockly-inspired (Pasternak et al. 2017) programming blocks already provided by the toolkit, we are creating age-appropriate AI blocks (Kahn et al. 2018) for students to use to complete AI-based programming challenges in PRIMARYAI. Together these blocks help introduce students to concepts such as image recognition, machine learning, and semi-autonomous navigation.

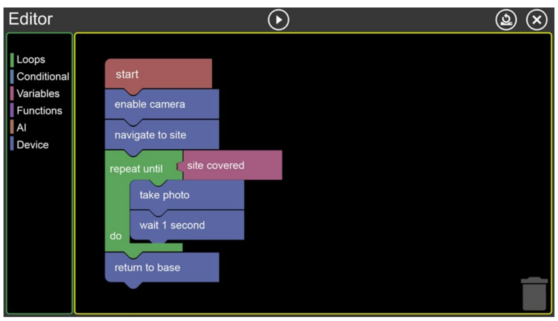

Figure 2: PRIMARYAI Block-based programming editor

For example, as described above, one quest presented to students in PRIMARYAI is to determine the cause of a recent decline in the population of penguins on an island using a semi-autonomous robot. This quest is broken down into smaller gameplay challenges that can be solved using the in-game block-based programming editor. The first step in this process involves programming the robot to gather photos around a defined exploration site (Figure 2).

After collecting the photos, students will review the photos with assistance from a virtual character to identify whether each photo gathered is a penguin, weasel, or something else by applying the appropriate label to the photo. Students learn that by identifying the images in this way, they are teaching the robot (training an algorithm and creating a classifier) to recognize patterns, so the robot will be able to distinguish different wildlife they are likely to encounter (Figure 3).

Once the robot's classifier has been trained to recognize the encountered wildlife, students will be encouraged to take the next step, program their robots to record the locations of encountered weasels (Figure 4).

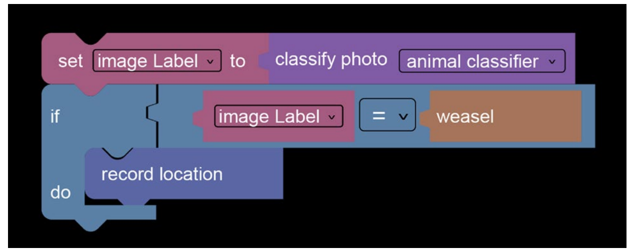

Figure 3: Block program for creating a classifier

Returning back to the students' base in the game, students will be able to visualize the location data gathered to discuss if the data supports whether the weasel population is negatively impacting the penguin population.

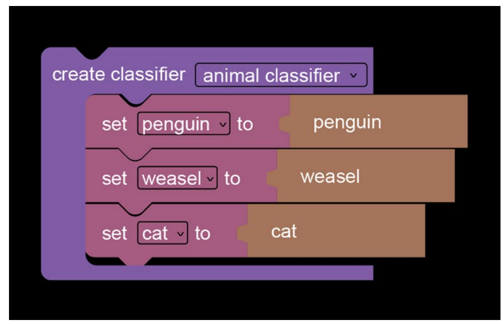

Figure 4: Using the classifier to track wildlife

Discussion

The game-based learning approach to AI-infused collaborative inquiry learning incorporates block-based programming within rich, problem-solving scenarios to support students' development of foundational AI knowledge. The approach offers significant potential for creating engaging collaborative learning experiences that integrate AI and life science.

Through our interviews with teachers, we have gained a better understanding of how to support them with integrating artificial intelligence into their classrooms. We analyzed the transcribed interviews and found, using a qualitative analysis method, that teachers will need more immersive and comprehensive professional development focused on AI content knowledge as well as grade level appropriate activities to deploy in the classrooms. Ideally, we believe that AI professional development workshops should provide follow-up classroom support to improve adoption and application of the professional development lessons and activities (Joyce and Showers 2002) as well as easy-to-implement, grade-level and age-appropriate exemplars. It is also important to note that striking the right balance between teachers co-designing, constraints of developing AI-infused game-based learning environments, and the lack of knowledge of teachers in the area of AI will present challenges for researchers.

The activities reported in this paper are only a first step towards introducing AI into upper elementary classrooms. The PrimaryAI game-based learning environment is still under active development and refinement, and it will be instructive to evaluate how it creates engaging and effective AI learning experiences.

Evaluating PrimaryAI

A key element of PrimaryAI's iterative design and development is evaluating its effectiveness in upper elementary classrooms. In addition to refining the system through the incorporation of key design elements from our partner teachers and students arising from our participatory co-design process, we are planning a series of classroom studies to test its effectiveness as we investigate the question: *In what ways does engagement with PrimaryAI support upper elementary students' learning artificial intelligence and life science*? Our evaluation will use a pre- and post-assessment design to measure the impact of PrimaryAI on student learning and engagement. The pre- and post-assessment items will cover key concepts in AI (e.g., decision making, classification, vision, and machine learning), AI ethics (e.g., unintended consequences, implicit bias), and life science (e.g., systems and cycles). From an engagement perspective, we are adapting coding schemes from Sinha et al. (2015) and Rogat (2019) for determining group engagement coded along dimensions of behavioral engagement (on-task participation), social engagement (responsive, equitable coordination), and emotional engagement (socio-emotional climate). We will conduct a content analysis of in-class discourse to investigate how teachers orchestrate student engagement with AI and life science content, as well as to investigate to what extent AI and life science content are embedded in classroom activities. We will also explore the relationship between student engagement and learning outcomes.

Conclusion and Future Work

AI is reshaping society. There is growing awareness of the need for K-12 students at all levels to learn about artificial intelligence. This is particularly true at the elementary grade level, since providing positive early learning experiences lays the foundation for future success. In this paper, we have presented an approach to introducing AI learning experiences into upper elementary classrooms. Guided by interviews with elementary school teachers to understand the types of support they need in integrating AI into their classrooms, it has been found that professional development focused on AI content knowledge as well as grade-level-appropriate activities will be critically important to successfully introduce AI into upper elementary classrooms. The PrimaryAI game-based learning environment aims to create engaging learning experiences centered around AI and life science. Integrating game-based learning and problem-based learning will enable PrimaryAI to support students in collaboratively learning about AI by engaging them in group-based problem-solving scenarios. PrimaryAI will support exploration of how to create engaging learning experiences that integrate AI and life science for upper elementary students as well as how to support elementary school teachers with integrating artificial intelligence and life science into their classrooms.

In the future, it will be important to further explore and refine how best to infuse AI concepts, such as perception, planning, robotics, and machine learning, into immersive problem-based learning experiences. Co-designing activities with both teachers and students will be important, as students are often left out of the instructional design process and their perspectives are often difficult for their teachers to predict. Conducting classroom studies to understand the strengths of game-based learning in supporting student learning around artificial intelligence, computer science, and life science will also be important.

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