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A review of AI teaching and learning from 2000 to 2020

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Abstract
In recent years, with the popularity of AI technologies in our everyday life, researchers have begun to discuss an emerging term "AI literacy". However, there is a lack of review to understand how AI teaching and learning (AITL) research looks like over the past two decades to provide the research basis for AI literacy education. To summarize the empirical findings from the literature, this systematic literature review conducts a thematic and content analysis of 49 publications from 2000 to 2020 to pave the way for recent AI literacy education. The related pedagogical models, teaching tools and challenges identified help set the stage for today's AI literacy. The results show that AITL focused more on computer science education at the university level before 2021. Teaching AI had not become popular in K-12 classrooms at that time due to a lack of age-appropriate teaching tools for scaffolding support. However, the pedagogies learnt from the review are valuable for educators to reflect how they should develop students' AI literacy today. Educators have adopted collaborative project-based learning approaches, featuring activities like software development, problem-solving, tinkering with robots, and using game elements. However, most of the activities require programming prerequisites and are not ready to scaffold students' AI understandings. With suitable teaching tools and pedagogical support in recent years, teaching AI shifts from technology-oriented to interdisciplinary design. Moreover, global initiatives have started to include AI literacy in the latest educational standards and strategic initiatives. These findings provide a research foundation to inform educators and researchers the growth of AI literacy education that can help them to design pedagogical strategies and curricula that use suitable technologies to better prepare students to become responsible educated citizens for today's growing AI economy.

Keywords AI teaching and learning · AI literacy · Pedagogy · Teaching tools · Systematic review

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1 Introduction

1.1 AI teaching and learning, and AI literacy education

Computer science education has a long history discussing how to teach students artificial intelligence (AI) in university education (e.g., robotics and software design, model construction, data structures). Teaching for AI can be traced to the 1970s when LOGO programming and Turtle robot was introduced to young learners (Papert et al., 1971). However, the tools actually focus more on computational thinking or programming concepts instead of AI. In 1995, "Artificial Intelligence: A Modern Approach" was published and this book was considered the most standard textbook in the field of AI for computer science undergraduates (Russell & Norvig, 1995). Computer science university students could learn how AI can solve problems, reason, learn, make decisions, communicate, perceive and act (Russell & Norvig, 1995). However, AI had not yet become an essential digital literacy and incorporated into K-12 computer curricula at that time, possibly due to a lack of developmentally appropriate teaching tools and pedagogy to scaffold students to develop AI understanding (Wang, 2021; Wangenheim et al., 2021).

Until 2016, the term "AI literacy" was first defined as the ability to understand the basic techniques and concepts behind AI products (Kandlhofer et al., 2019). Recent researchers associate AI literacy with other skills including communication and collaboration using AI (e.g., Long & Magerko, 2020; Ng et al., 2021a, b). Long and Magerko (2020) referred AI literacy to digital competencies necessary in which AI transforms the way that we communicate, work, and live with each other and with machines. Ng et al. (2021b) proposed the use of Bloom's Taxonomy to conceptualize AI literacy that learners are no longer merely end users, they should be able to reach higher cognition levels to communicate, collaborate and create with AI. Ng et al. (2022a) further introduced AI literacy as an important technological skill in the twenty-first century and revised the P21's framework to prepare students with higher levels of knowledge and skills, and other thinking skills (e.g., multidisciplinary skills, collaboration, creativity, lifelong learning skills). Schools need to innovate in regard to pedagogy, curriculum and teaching tools to foster learners' AI literacy.

In recent years, there has been renewed interest in introducing AI to K-12 students (Long & Magerko, 2020), and non-computer science university students (Kong et al., 2021). This is fuelled by the availability of easy-to-use AI-empowered teaching tools such as Tensorflow Playground, Teachable Machine, and AI for Ocean in Code.org (Wangenheim et al., 2021). Many of these platforms enable non-technical students to generate machine learning models without computer science prerequisites (Wangenheim et al., 2021). This makes teaching AI no longer as difficult as it was in the past. Educators have started to engage non-computer science undergraduates, and even K-12 students in learning about AI (Chai et al., 2021; Chiu & Chai, 2020; Xia et al., 2022). Students are not merely consumers of AI applications, but creators of intelligent solutions which require teaching the AI concepts behind (e.g., developing image recognition models) (AIK12, 2019; Ng et al., 2021a, b).

Global initiatives (e.g., ISTE, UNESCO, DigComp) have started to conceptualize AI literacy according to the latest educational standards and design guidelines to address digital literacy levels across the globe (DigComp, 2022; ISTE, 2022; UNESCO, 2021). These frameworks represent different perspectives toward the idea of AI literacy. UNESCO (2021) reported that eleven countries around the world have incorporated AI into their STEM/computing curricula to promote competitiveness and equip young people for the future workplace. AIK12 (2019) proposed the "five big ideas" about AI that serve as the framework to uncover the necessary AI concepts that students in each grade level should learn. The five big ideas include perception, representation and reasoning, learning, natural interaction, and societal impact of AI (AIK12, 2019). The ISTE (2022) further designed an AI project guideline and proposed seven standards to prepare students to become (1) empowered learners, (2) knowledge constructors, (3) computational thinkers, (4) innovative designers, (5) digital citizens, (6) creative communicators, and (7) global collaborators. With curricula, teachers can empower their students' AI competencies, attitude and readiness, to communicate with other learners, solve authentic problems, develop ideas and theories and solutions innovatively and collaboratively (ISTE, 2022). DigComp (2022) modified its framework to accommodate AI technologies to facilitate educators to propose six categories to enhance their (1) professional interactions with different parties using AI, enhance educators pedagogical competencies including (2) digital resource management, (3) teaching and learning, (4) assessment, and (5) teaching strategies to empower learners, so as to (6) facilitate learners' AI competency. These frameworks make for easier understanding and implementation of AI literacy education to help educators, researchers and governments to design suitable strategies and learning programs to prepare learners to be digitally competent in AI knowledge, skills and attitude.

1.2 Current status of AI learning and teaching

Developing students' AI knowledge and skills has been implemented in different ways with government and university efforts. Governments have recognized the need for AI literacy programs from K-12 to higher education (UNESCO, 2019). National AI strategic plans have been established in various countries including the United States, China, and Germany (Laupichler et al., 2022; Ng et al. 2021a). Researchers have started to conduct empirical studies to report on informed learning projects (e.g., Lee et al., 2021; Ng et al., 2022a; Williams et al., 2019) and formal curricula (Xia et al., 2022) in primary and secondary schools. Some pilot schemes such as "AI for the Future" in Hong Kong (Chiu et al., 2021), and the DAILy Curriculum from the USA (Van Brummelen et al., 2021) to develop AI literacy for secondary students. Moreover, various approaches such as digital story writing (Ng et al. 2022b), experiencing AI through toys and robotics, (Yang, 2022) and visualization tools (García et al., 2006) were introduced to support young children to learn about the possibilities of AI at an early age. Furthermore, universities have started to introduce AI to non-computer science university students (Kong et al., 2021; Ng et al., 2022a) such as medicine, business administration, and teacher education to get ready for their future workforce (Laupichler et al., 2022).

Exploratory reviews have started to summarize the effective practices of teaching AI across different levels. For example, Su et al. (2022) conducted a meta-review to examine 14 research papers on AI curriculum for K-12 classrooms that were taken in the Asia–Pacific region from 2018 to 2021 and identify the content knowledge, tools, platforms, activities, theories and models, assessment methods, and learning outcomes. Laupichler et al. (2022) reviewed 30 studies from 2016 to 2022 to understand AI literacy in adult education as well as what content should be taught for non-technical learners. Ng et al. (2021b) adapted the TPACK model to explain how teachers design suitable pedagogical approaches and technologies for their learners. Wangenheim et al. (2021) presented a ten-year systematic mapping of emerging visual tools from 2010 to 2020 to support the teaching of machine learning in terms of educational characteristics, deployment and how the tools have been developed and used to teach students AI (e.g., Scratch, App Inventor, mblock, Google Teachable Machine, RapidMiner). Sanusi et al. (2022) identified the four major categories of teaching resources and tools (conversational agents, programming environment, robotic, and unplugged activity) in K-12 settings based on 38 studies from 2010 to 2021. Ng et al. (2022a) reviewed how to teach and learn AI from kindergarten to university level from 2016 to 2022 in terms of pedagogy, teaching tools, learning content and assessment methods, and proposed the use of the P21's framework for twenty-first century learning to describe the AI literacy skills and knowledge students must learn to succeed in work and life.

2 Research motivation and aim

There are review papers that summarize the pedagogy, learning content and teaching resources to foster students' AI literacy. Among the review articles, only two of them present ten-year reviews and present AI teaching resources (Sanusi et al., 2022; Wangenheim et al., 2021), and only one discusses pedagogies used to teach students AI (Ng et al. 2021b). Most of the studies focused on recent years instead of constructing longitudinal literature reviews. In fact, recent reviews have tried to look back on the history of AI in education over the past two decades to pave the way for AI education (e.g., from 2000 to 2019, Chen et al., 2022; from 2012 to 2021, Tan et al., 2022). However, there are no existing reviews tracing back the history of teaching AI to the last two decades. Through reviewing material from earlier works, educators can make the delivery of computer science education more relevant, improve students' learning experiences positively and inform non-technical elements within their computing specialties (Impagliazzo, 2020). To reduce this research gap, this review aims to inform educators and researchers how AI was taught throughout twenty years that guides for their future research and instructional design.

Furthermore, the term "AI literacy" was introduced in 2016; however, it has not become popular at that time. According to a search from January to December 2021 in Web of Science and Scopus databases, there are 23 papers (i.e., paper number 50

– 71) published in 2021 using the same selection criteria of this review (see Appendix Table 5). It is interesting to note that there were around one to five papers per year over the two decades and, even in 2020, only four papers were published. Until 2021, the number of AITL publications increases sharply within a year. As such, it is proposed that 2021 is the breakthrough year of AI (e.g., Ng et al. 2022a; Sharma, 2021), and AITL has then transformed to a new understanding (i.e., AI literacy) this year. Since 2021 is considered as the beginning year of the AI literacy era, this article reviews until the year 2020 to document the previous AITL experience to pave the way of AI literacy education.

To our knowledge, most of the studies focus on the current status of AI teaching and there is no review to summarize how teaching AI looks like over the past twenty years. To give a foundation for recent AI literacy research, this review traced the AITL situation back to 2000 to shape today's AI literacy education through analyzing 49 AITL studies in the Web of Science and Scopus databases from 2000 to 2020. Readers can understand how AI was taught in the past, and, together with recent reviews, they can update the most current situation to inform educators how AI literacy looks like today. According to the three research questions, this review is interested in the learner types, teaching tools and pedagogical approaches used in AITL.

The first research question identified the trend of teaching AI. Researchers claimed that teaching AI has suddenly become popular in primary/secondary and non-computer science university education (e.g., Chai et al., 2021; Lin et al., 2021; Ng et al. 2021a, b). This review provides evidence to support the claim by identifying the learner types in the selected studies. The second and third questions look at areas of pedagogical approaches and teaching tools used in the selected studies. Researchers attribute the popularity of teaching AI to the rise of teaching tools and pedagogy (Xia et al., 2022; Ng et al., 2022a). Therefore, this review summarizes the development of teaching tools and its related pedagogical strategies that have been commonly used in the past studies. In this way, readers can understand what teaching challenges and good practices teachers have had in the past to further provide insights for today's educators to design their instruction for AI literacy education. After all, this review can usefully contribute by laying a foundation for AI literacy research, which provides a concise reference for policymakers, school leaders and educators. Three research questions (RQs) are as follows:

RQ1 What are the common types of learners in AITL?
RQ2 What teaching tools have been used in AITL?
RQ3 What pedagogical approaches have been commonly used in AITL?

3 Methods

3.1 Search and manuscript selection process

To understand the development of AITL research, this study has included both peer-reviewed scholarly articles and conference papers regarding how to teach and learn AI in K-16 education. The survey has considered works published from 2000 to 2020, as found on the Web of Science and Scopus Databases. These databases are selected since they are two most trusted platforms for citation indices regarding evidence-based scientific research. The works included in these databases are deemed to present scientific content of high quality and significant impact. First, we searched the articles published in the two databases from 2000 to 2020 according to the phrase ("AI" OR "Artificial Intelligence" OR "Artificial Intelligence literacy" OR "Deep learning" OR "Machine learning" OR "Neural network" OR "Natural language processing" OR "Chatbot") AND ("learning" OR "teaching" OR "K-12" OR "students" OR "universities" OR "higher education" OR "children" OR "STEM education" OR "curriculum" OR "course") in either the title, the abstract, main text or keywords were downloaded and reviewed.

On 31 December 2020, 10,822 articles were discovered in the first search. Our researchers downloaded the articles from the two databases using the keywords in their titles and abstracts. The first and second authors examined the selected articles to determine whether they were suitable for this study. We adopted a set of inclusion and exclusion criteria to ensure generalization of the findings and to avoid biases in the study selection (see Table 1). All artificial intelligence in education (AIED) papers are excluded since it does not focus on how to teach and learn AI to offer insights for educators. For example, Hind et al. (2019) was excluded as it focused on AIED system architecture, instead of teaching and learning AI. As such, a total of 49 articles met the criteria for this review. Moreover, other review and discussion papers were excluded. For example, Touretzky et al. (2019) was removed because it was not an empirical study but a discussion paper giving an overview of AI-related ideas. Although Touretzky et al. (2019)'s paper is not analyzed according to thematic analysis in this review, insights generated are discussed to develop guidelines for teaching AI for K-12 students. After excluding the irrelevant studies, a total of 49 articles were identified. An overview of the search protocol is presented in a PRISMA diagram (see Fig. 1). Appendix Table 5 lists the publication information of the selected articles and Appendix Table 6 summarizes the study purposes, content knowledge, pedagogy, teaching tools and key findings of each study.

Table 1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
(1) The studies had to be empirical papers, articles, case studies or conference proceedings published in journals indexed by the Web of Science and Scopus databases (2) The studies had to be empirical, practical, evidence-based and conducted in primary, secondary or higher education settings (3) The studies had to provide descriptions of the underlying theories and methods used	(1) Review, editorials and theoretical papers were excluded because they are not empirical studies (2) Articles that mentioned the term "artificial intelligence" but were actually about using AI in education or other fields were excluded

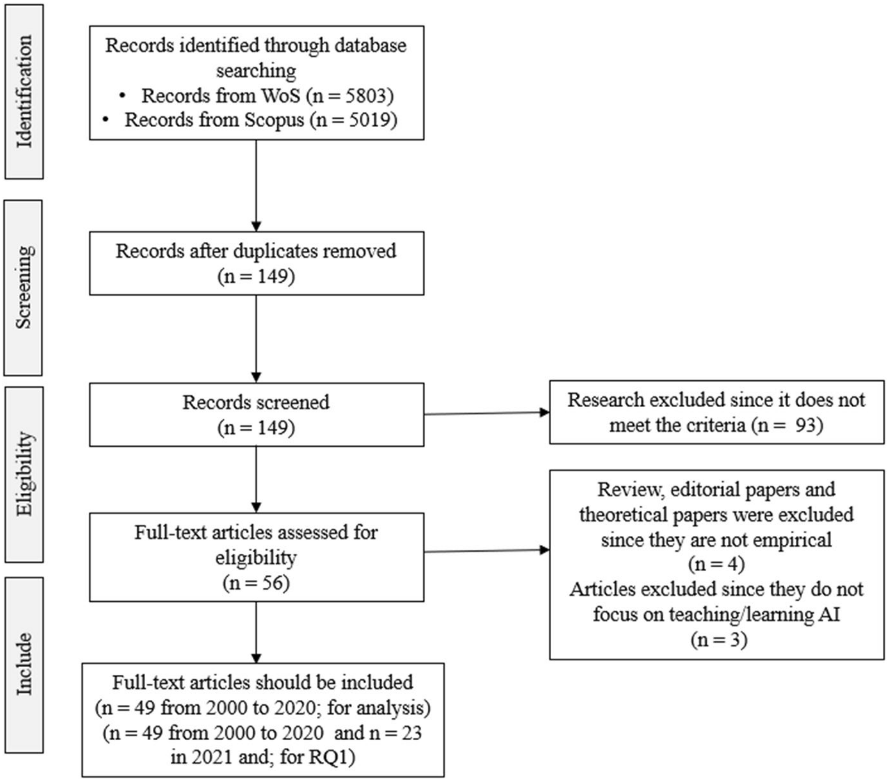


Fig. 1 PRISMA diagram

3.2 Data coding and analysis processes

This study began by formulating objectives, followed by a review and analysis of AITL research trends in terms of their methodological approaches, fields of study, purposes, theories, platforms and effects. The relevant articles were qualitatively classified using the constant comparative method espoused by Glaser (1965), as has been done in other recent systematic reviews (e.g., Hew & Cheung, 2014; Williams et al., 2013). The first and second authors independently coded 33 (68.75%) randomly selected articles in a scheme to establish inter-rater reliability. For example, to categorize the pedagogical approaches used in AITL, they first agreed on the definitions of different approaches and selected samples for each approach from the studies to develop a scheme. After classifying the rest of the articles based on the scheme, an inter-rater agreement was calculated. The researchers had more than 80% inter-rater agreement on each research question with Cohen's kappa coefficient (0.85) which showed a good inter-rater reliability (Miles & Huberman, 1994).

Inductive thematic analysis was used and grouped patterns of shared meanings into themes in terms of pedagogies and learning tools. In cases of discrepancy, the coders resolved any differences through discussion.

4 Research background

This section first illustrates the background information including publication year, country, levels of education, and research method of the 49 selected studies. Appendix Table 5 displays the selected articles from the Web of Science and Scopus databases.

The publications of AITL papers were few in each year from 2000 to 2020 (see Fig. 2). There are only one to five papers per year. We can see that AI literacy has not still gained much attention in the first few years since the term first mentioned in 2016. Until 2021, the number of publications grew rapidly to 23 to examine different interventions to inform educators how to teach K-12 students about AI (e.g., Long & Magerko, 2020; Ng et al., 2021a, b). Since then, AI literacy has gained popularity and countries have endorsed AI curricula to foster students' necessary digital competencies. Therefore, we propose that 2021 is the "breakthrough year of AI teaching".

To understand the situation of AITL before 2021, the country/regions of the first author in the selected studies was listed. The countries/regions that published two or more articles are: the United States ($N=25$), Spain ($N=6$), the United Kingdom ($N=2$), Canada ($N=2$), Hong Kong ($N=2$) and Thailand ($N=2$) (see Fig. 3). The number of AITL publications in the USA is the highest.

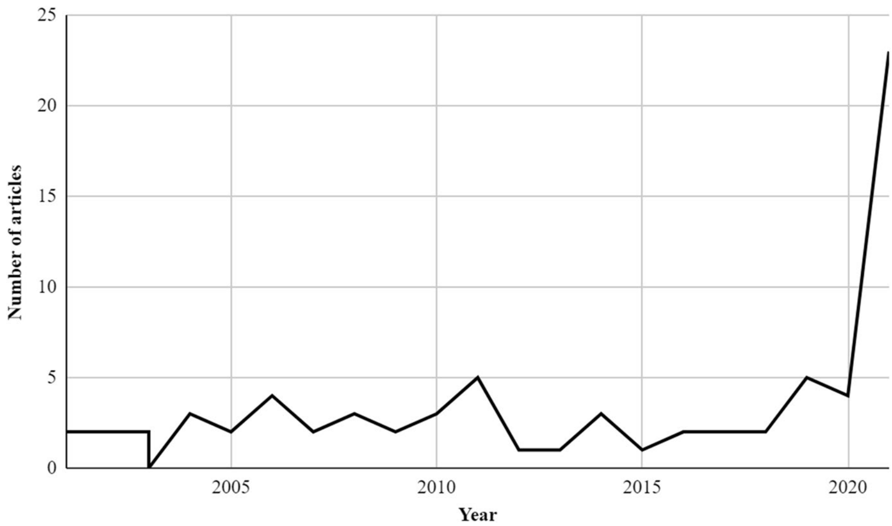


Fig. 2 Years of publication

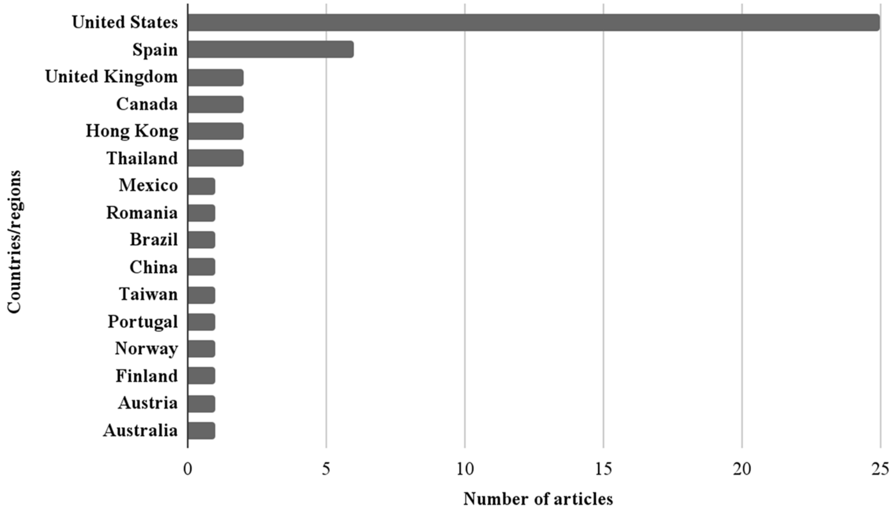


Fig. 3 The numbers of AITL studies by country

Regarding the research methods used, 20 of the selected studies (40.8%) sought to investigate the AITL field by using exploratory methods that involved narrating and documenting instructional designs (N=16) or curricula (N=4) (see Table 2). Most studies are found to be preliminary studies. They sought to explicitly describe learning outcomes as they occurred via observational data and descriptive documentation, without rigorously measuring students' learning outcomes (Stebbins, 2001). Other researchers began to apply in-depth methodological approaches to implement evidence-based practices. Among the articles using such approaches, 12 (24.5%) used a mixed-methods approach to collect data via multiple sources, including tests, questionnaire surveys, assessments, interviews and observations (see Fig. 4). Nine of the articles (18.4%) used rigorous qualitative approaches such as active observation, in-depth interviews and focus group interviews for interpreting the lived AI learning experiences and perceptions of both teachers and students. Last, eight studies (16.3%) adopted quantitative methods via questionnaire surveys and assessment tests. In the near future, there is a need for AI educational research to shift to be more empirical and interventional (e.g., quasi-experiments, design-based research) with clearly documented treatment and control groups and varied data analysis procedures (e.g., regression, structural equation modeling, t-test, ANOVA).

Concerning the data collection techniques, nearly half of the selected AITL studies collected observational data for empirical evaluation (N=29, 42.0%) (see Fig. 4). Generally, the data sources used in these studies included student questionnaire surveys (N=20), assessment tests (N=7) and teacher perception interviews (N=3). Such methods provided insufficient data to allow critical evaluations of the effectiveness of the AITL initiatives considered. We can see that there is a lack of assessment methods to examine students' learning outcomes. Future studies are necessary to design appropriate assessment methods to examine and triangulate students' learning performance to further improve the instructional implementation.

Table 2 Methodological approaches

Data sources/ methods	No. of articles	Studies
Exploratory qualitative studies	20	Wong et al. (2010); McGovern et al. (2011); Kumar (2001); Kumar et al. (2006); Wolfer (2019); Swoboda et al. (2011); League (2008); Kozak (2006); Bryce (2011); Narahara & Kobayashi (2018); García et al. (2006); Kandlhofer et al. (2019); Li et al. (2014); DeNero and Klein (2010); Hill & Alford (2004); Hartness (2004); Sánchez-Nielsen & Klink (2011); Mota-Valtierra et al. (2019); Chiu & Chai (2020); Cicirello (2008); Sabuncuoglu (2020)
Mixed methods	12	Popescu & Badica (2011); Wallace et al. (2010); McGovern & Fager (2007); Estevez et al. (2019); Pantic et al. (2005); McKee (2002); Scheessele & Schriefer (2006); Dodds (2008); Michaud (2014); Barik et al. (2013); Sakulkueakulsuk et al. (2018); García et al. (2006)
Qualitative	9	Chiu & Chai (2020); Klassner (2002); Imberman (2004); Imberman (2005); Chiang (2007); Weidong et al. (2009); Merzbacher (2001); Toivonen et al. (2020); Albu (2012)
Quantitative	8	Carpio Cañada et al. (2015); Fernandes (2016); Straub et al. (2017); Silapachote & Srisuphab (2014); Ribeiro et al. (2009); Chai et al. (2020); Sintov et al. (2016); Goel & Joyner (2017)

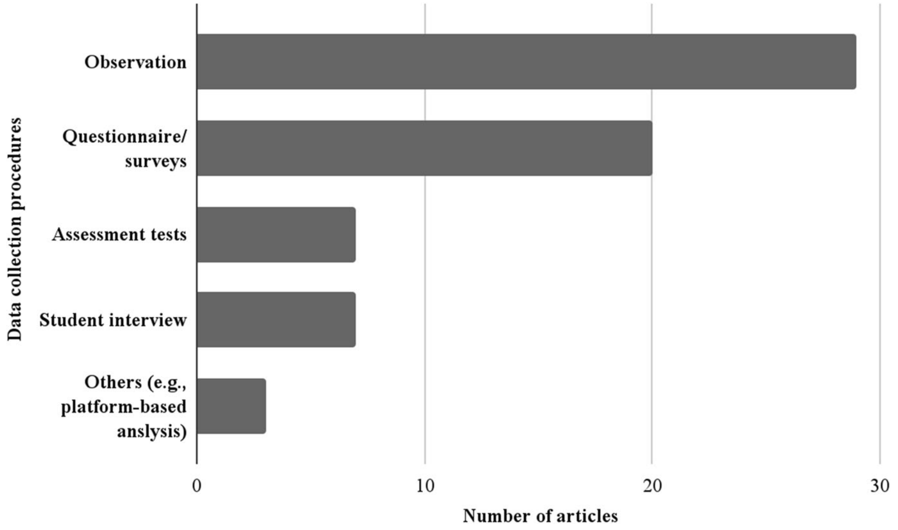
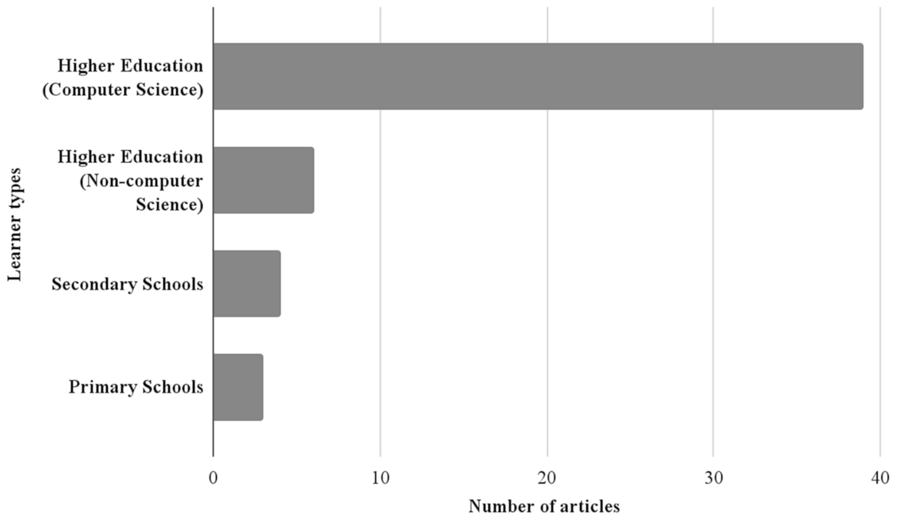


Fig. 4 Distribution of data collection procedures

5 Results and discussion

5.1 RQ1: What are the common types of learners in AITL?

Higher education. Out of the 49 studies reviewed, 39 were carried out with computer science undergraduates (see Fig. 5). Only a few studies were conducted to



Remarks: Studies can be conducted at more than one educational level.

Fig. 5 Distribution of learner types. *Remarks:* Studies can be conducted at more than one educational level support non-computer science students in universities *(N=9)* to have preliminary programming and AI experience. For example, Merzbacher (2001) designed an AI course that catered to both computer science majors and non-majors by replacing programming tasks with exercises in mathematical logic or with projects to explore AI applications in their own disciplines (e.g., history, music, education). Both computer science majors and non-majors reflected that they had learned a great deal from these courses (Merzbacher, 2001). The study presented various technical topics in AI, ranging from expert systems to neural networks, without requiring any programming or mathematics background through hands-on exercises and software demonstrations. Although students reported that the 14-non computer science students meet some technical difficulties when learning AI, they found the course both accessible and interesting (Merzbacher, 2001). Another study conducted by Cicirello (2008) focused on non-computer science students as part of a liberal arts curriculum. In the course, students can learn Turing and AI, philosophy of mind, human-like problem solving, collective problem solving, and natural language communication. The study showed that the non-computer science students could also learn the fundamental AI elements from a liberal arts perspective.

Primary and secondary education Teaching AI was not popular in primary and secondary education before 2021. There are three studies in a primary school setting and four studies in secondary education. The first article that identified the two study levels is conducted by Narahara & Kobayashi (2018). This study introduces AI and robotics to beginning learners through playing and testing in a virtual learning environment, training an AI model based on data sets acquired from the virtual testing, and running a toy car using the trained AI model on a track. The study showed that students can experience basic AI knowledge such as neural networks and image recognition, and enhance their curiosity and motivation to learn AI (Narahara & Kobayashi, 2018). Another study conducted by García et al. (2006) used a visualization tool called Machine Learning for Kids and Scratch (a blockly-based programming) to develop children's machine learning concepts through training datasets. Toivonen et al. (2020) made use of Google Teachable Machine to teach students machine learning principles among primary students to design their intelligent solutions. This tool was a feasible and mature tool for learners without previous experience in programming. The study identified that young learners may not have enough technical knowledge and skills, and large datasets to build AI-empowered solutions with high prediction accuracy. However, the activities can effectively foster students' AI knowledge and skills behind (e.g., sound and object detection, neural networks) (Toivonen et al., 2020). Although not all students need to turn out to be computer scientists, it is important for students to develop necessary knowledge, skills and attitudes to become digitally ready and facilitate their study and daily life (UNESCO, 2019).

Few studies were conducted at the primary and secondary school levels, and most studies focused on computer science university education over the past two decades. A reason is that teaching AI was not popular before 2021 due to a lack of age-appropriate learning technologies, and comprehensive AI curriculum to scaffold young learners' AI knowledge and skills (Merzbacher, 2001; Sakulkueakulsuk et al., 2018). Most of the identified studies took place in computer science higher education settings. The lack of age-appropriate learning technologies is a major barrier for young learners and non-computer science students to learn AI (Ng et al. 2021b). In the past, students were required to use syntax programming to make neural networks, intelligent agents and classification models, which is not possible for novices. Nowadays, with more developmentally appropriate learning tools, students can use block-based programming to create their AI-driven artifacts (Long & Magerko, 2020).

5.2 RQ2: What teaching tools have been used in AITL?

The most common type of teaching tools used in AITL were platforms for software development ($N=21$) (see Fig. 6). Such platforms were used for either game design ($N=16$) or programming activities ($N=5$). Some of the reviewed studies used more than one teaching tool. Robotics (N = 18) was the second most prevalent type of teaching tool in AITL designs. Robots with programmable tangibles, such as sensors, buttons and display panels, were commonly used in curricula to solve various problems. With the creation of AI-enabled technologies, intelligent agents (e.g., expert systems, machine learning trainers, chatbots) ($N=7$) have become increasingly popular. These agents have enabled students to build custom machine learning models without prior knowledge of coding. Table 3 lists the first appearances of teaching tools in the selected studies, presented in chronological order. Figure 7 displays the teaching tools used in primary, secondary and higher education. Appendix Tables 7 and 8 further shows the details regarding teaching tools.

Software development can be learned through various tasks, such as game design, tinkering and programming with syntax/block-based programming languages (Weintrop & Wilensky, 2015) or by using multimedia elements and

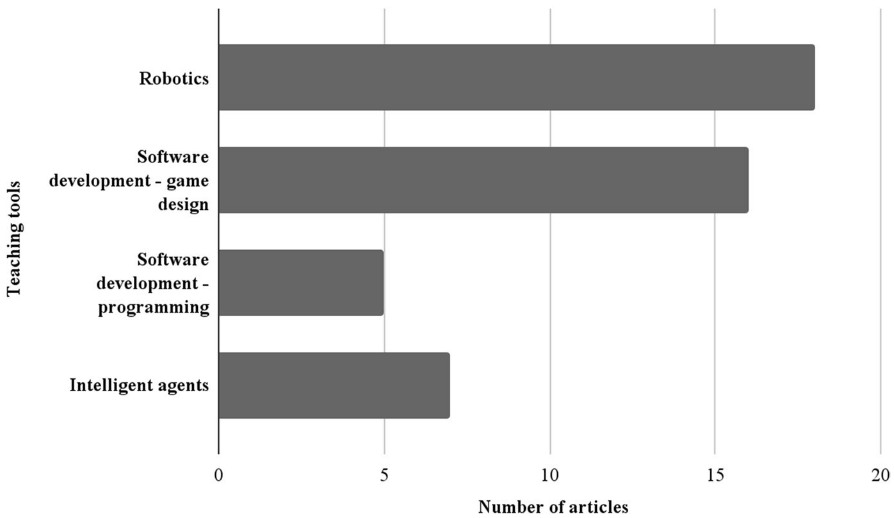


Fig. 6 Teaching tools used in the selected articles

Table 3 Timeline of AI teaching tools

Year of first appearance	Teaching tools
2001	Lego robot
2002	Internet-based online robot
2004	Pathfinders, sensors, robots made to do specific tasks, Robocode
2005	Java-based agents, chatbots, puzzle boards/ grid games
2006	Python programming, poker-playing agents, avatar movement, expert systems, data mining
2007	Spacewar simulation, Pacman
2008	Connect4, Sudoku
2009	MATLAB
2010	Pinball machine
2011	Adaptive learning system, Google developer kit
2012	Quizzes with video clips
2017	Intelligent tutors
2018	User interface (UI)-based software for machine learning, RapidMinder, Mango ML model
2019	Scratch, biomedical applications, PhysioNet, Machine Learning for Kids, Robotic arms
2020	Computer vision, Google Teachable Machine

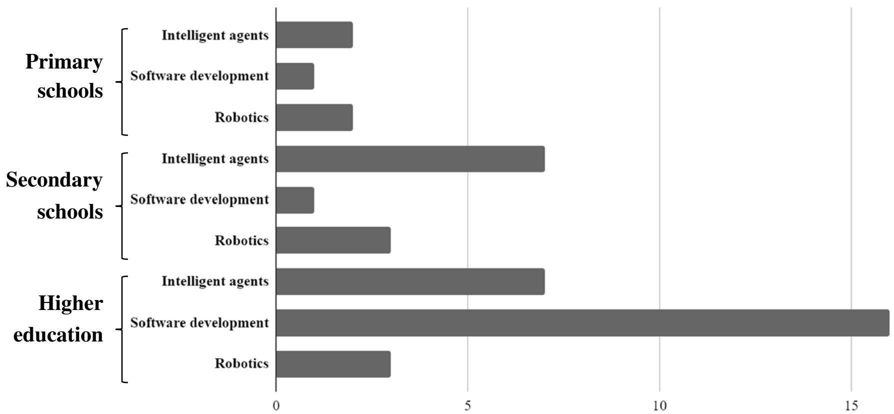


Fig. 7 Teaching tools

simulation demonstrations to visualize computer science concepts (Shaw, 2000). Twenty-one of the selected studies (42.9%) adopted these types of teaching tools to scaffold students' understandings of AI. For example, Merzbacher (2001) used simulation games and demonstrations (e.g., chess, tic-tac-toe) and rule-based or statistical simulations (e.g., translation, Markov models) to illustrate the AI concepts behind functions such as informed searches, machine learning, genetic programming or natural language processing. Another study by Albu (2012) used interactive videos and mobile apps to illustrate AI principles and techniques such as clustering, computer vision and game theory. Albu's study involved an AI online course that included over 20,000 students. Approximately 90% of these students reported that this online learning experience, with its rich digital artifacts, strengthened their AI learning.

Robotics was used in 36.7% of the selected AITL studies ($N = 18$), and the participants found this approach effective for enhancing cognitive gains and motivation. Robotics offers students hands-on experience with combining software and hardware components to control their robots. Such experience was found to enhance the students' motivation for learning and their cognitive gains. For example, Carpio Cañada et al. (2015) designed an online robotics competition that significantly consolidated the students' theoretical concepts, improved their perceptions regarding the value of AI courses, promoted their motivation and interest and developed their personal skills. The participating students significantly increased their average grades following their experience making online robotics.

Swoboda et al. (2011) observed that Lego and virtual robotics can effectively motivate students to gain essential skills in the areas of advanced searching (e.g., heuristics, genetic algorithms), machine learning (e.g., neural networks) and robotics (e.g., sensing, world models, planning, navigation). According to these researchers' observations, using realistic problems and real robots strongly motivated the students to learn, work hard and produce high quality work. Kumar (2001) also found that using Lego robots was an effective way to make AI learning more interesting and engaging. Using robots also helped to engage the students in learning about AI concepts, and it offered them opportunities to apply and implement those concepts. In the survey by Fernandes (2016), 86% of the participating students ($N = 85$) reported believing that the IRobot platform (for simulation of mobile robotics) helped them to acquire new skills for developing AI solutions.

Intelligent agents are a type of software that works autonomously to help students gain knowledge and build inquiry skills through AI-enabled tools such as pattern recognition systems and chatbots (Peña et al., 2005). Our review found that 14.3% of the identified AITL studies ($N = 7$) adopted intelligent agents to help students learn about AI. For example, Sakulkueakulsuk et al. (2018) used RapidMiner, a Web-based agent, to generate machine learning models. They engaged secondary school students in constructing machine learning models by applying interdisciplinary knowledge to predict the sweetness and quality grades of mangoes. Such STEM instructional strategies have been proven to successfully engage students, as activities that are deemed fun and interactive are effective in helping students to gain essential skills such as futuristic thinking and interdisciplinary thinking, as well as a better appreciation of AI.

Goel and Joyner (2017) adopted AI-enabled intelligent tutors that offered automated evaluation and feedback. These tutors helped to guide students in conducting authentic collaborative projects that significantly enhanced the students' AI abilities. Another study by Toivonen et al. (2020) used Teachable Machine, a machine learning Web application powered by convolutional neural networks, to provide an easy-to-use yet powerful tool for primary school students to explore and design machine learning models through classification tasks. The researchers observed that although the predictive accuracy of the students' models was generally low, they were able to use their mobile devices to test and play with the AI-enabled applications despite their limited programming experience.

5.3 RQ3: What pedagogical approaches have been commonly used in AITL?

Successful teaching not only depends on teaching tools as the drive, but pedagogies are also important to meet students' needs to motivate them to learn AI. Recent studies/reports have recommended useful pedagogical guidelines for teachers to develop students' AI literacy (e.g., ISTE, 2022; Long & Magerko, 2020; UNESCO, 2019). For example, Long and Magerko (2020) proposed the need to leverage learners' interests and reduce entry barriers through playful game experience when designing AI literacy interventions. Moreover, researchers should consider AI learning experiences that foster students' social interaction and collaboration through projects. Practical guides for educators are proposed to engage students in creating AI artifacts via authentic projects (ISTE, 2022). These considerations give a lens to understand how these pedagogies fit into the goal of teaching students to become AI literates. This section focuses on the two major pedagogies identified in the selected studies: collaborative project-based learning, and learning with game elements (see Table 4).

The first pedagogy combines the advantages of collaborative learning which enable students to communicate and collaborate with others (Long & Magerko, 2020), and solve authentic problems through project-based learning (Kong et al., 2021). After that, playful game experience is considered as a low barrier to developing AI concepts among beginning learners who do not have extensive backgrounds in computer science, and sustain their motivation in learning AI (Long & Magerko, 2020; Ng et al., 2021a, b).

5.3.1 Collaborative project-based learning

A common trend identified among the articles reviewed was the popularity of collaborative learning activities that involved project-based learning. We found that 61.2% ($N=30$) of the articles concerned collaborative curricula designs, and that 85.7% ($N=42$) of the articles adopted the project-based learning approach. These collaborative project-based learning programs tended to incorporate technological teaching tools such as robotics or game elements. Such tools provide an interactive medium for students to work collaboratively in groups using experimentation to tinker with physical artifacts and conduct trial-and-error or iterative refinements (Mota-Valtierra et al., 2019; Sakulkueakulsuk et al., 2018). This approach provides students with opportunities to build teams and apply what they have learnt and co-construct their understandings of AI.

The studies that adopted a collaborative learning approach recognised the importance of developing students' interests, abilities and social skills. For example, Kumar (2001) found that over 90% of participating students strongly supported the use of Lego MindStorms robot group projects for teaching AI and computer science concepts such as heuristic searches or depth- and breadth-first searches. McGovern et al. (2011) claimed that 15% to 30% of the students grew more creative and sought to gain extra credit on their solutions by conducting A* searches when doing Java-based game design group projects. In another study, Carpio Cañada et al. (2015) explored

Table 4 Pedagogical approaches

Pedagogical approach	Definition	Number of articles	Sample studies
Collaborative learning	Learning approaches involving joint intellectual effort by learner groups to solve problems, complete tasks or create products (Linden et al., 2000)	30	Mota-Valtierra et al., (2019); Wallace et al. (2010); Carpio Cañada et al. (2015)
Project-based / problem-based learning	Learning approaches that engage students in gaining knowledge and skills by working to investigate authentic questions, problems or challenges either individually or in groups (Krajcik & Blumenfel, 2006)	42	Kumar et al. (2006); McGovern et al. (2011); Michaud (2014)
Learning with game elements	Learning approaches that involve game elements such as game design, game-based learning and gamification, which enhance students' understanding, interest, motivation and engagement (Kapp, 2012)	24	Chiang (2007); Ribeiro et al. (2009); Wong et al. (2010); Li et al. (2014)

Remarks: A paper can have more than one pedagogical approach the use of game design and intelligent agents by groups participating in the Google AI Challenge. They found that the students made significant gains in their knowledge of AI, their motivation for learning and their skills in cooperation and organization. These findings showed that students could potentially benefit from collaborative learning that develops their social support, willingness to learn and practical abilities in a student-centered learning community (Laal & Ghodsi, 2012; Linden et al., 2000).

5.3.2 Game elements

Game design has been a promising approach to learning software development that interests K-12 students in computer science education (Leonard et al., 2016). Our analysis found that nearly half of the reviewed studies ($N=24$) demonstrated positive effects (in terms of learner engagement or motivation) from using game elements in their instructional designs. Through building games, the students learned to apply gamified elements (e.g., leaderboards, performance graphs, avatars). They also learned to apply AI and computer science concepts in designing their games' rules and in testing their games by playing them (Sailer et al., 2017). Although game design differs from gamification or game-based learning, the students could reap the benefits of gamification in terms of enhancing their understanding and their levels of interest, motivation and engagement (Zainuddin et al., 2020; Ng & Chu, 2021). For example, Wallace et al. (2010) found that students gained a stronger perceived ability and interest through using game-playing agents and tile-based games. In another study, Ribeiro et al. (2009) designed a competition in tile-based game development by using Ataxx. Approximately 90% of the 37 participating students believed that the game development platform, competition-based approach to learning and Prolog programming environment effectively enhanced their understanding of AI concepts and improved their motivation for learning. These findings provide evidence that adding game elements to AI curricula not only makes complex AI concepts less intimidating but also addresses the various psychological needs associated with self-determination theory regarding motivation, thereby increasing students' interest and engagement (Ng et al., 2021a, b).

6 Discussion

6.1 Challenges of teaching AI in the past for non-technical learners

This review provides a summary of how AI was taught over the past two decades that pave the way for AI literacy education. According to the first research question, teaching AI was not popular among primary and secondary school students before 2021. Several barriers to AITL were noted by researchers and educators.

One key challenge that instructors of AI courses faced was the visualization and presentation of complex AI concepts in ways that can be applied to everyday computing tasks and problems (Kozak, 2006). Another issue was how to provide adequate scaffolds to enhance students' achievements, abilities and literacy in AI (Hartness, 2004; Estevez et al., 2019). Especially for beginning learners, AI concepts can be difficult for primary and secondary students, as well as non-computer science students to grasp because of knowledge disconnects between the AI concepts and their daily experiences. Additionally, syntax-based programming languages used in AI courses, such as LISP and Prolog, have raised barriers to understanding as students often find it challenging to relate their codes to the software applications (Kozak, 2006). Therefore, some teachers have turned to newer technologies, such as block-based programming or simulation tools such as QuickDraw, Code.org and Teachable Machines in recent years. These ease-to-use tools and applications can help students to assimilate AI concepts without learning syntax-based programming. Third, many teachers, especially those in primary and secondary settings, reported a lack of confidence in their own understanding because the field of AI is changing rapidly, and they often lack access to relevant technological pedagogical content knowledge. However, with appropriate teaching tools, teachers can integrate suitable pedagogical approaches to scaffold students' AI understanding and help students reach higher cognition levels such as co-creating intelligent agents with peers. Moreover, future efforts are needed to have closer partnerships between governments, educators and researchers in designing curricula and improving the professional development process to equip teachers with technological pedagogical content knowledge to become more ready to teach AI.

6.2 Growth of age-appropriate teaching tools and pedagogies

As discussed in the second and third research questions, the popularity of teaching AI can be attributed to the emergence of age-appropriate pedagogies and teaching tools. This review article identified that collaborative project/problem-based learning and game elements are useful for students to connect technical solutions with authentic problems in an engaging way. With more teaching tools such as robotics kits, intelligent agents and interactive platforms, students can understand and apply AI concepts without technical background (García et al., 2006; Toivonen et al., 2020).

In the past, prior educators faced challenges in providing meaningful scaffolding for students to learn about AI concepts and algorithms through various syntax-based programming languages, especially for primary and secondary school children (e.g., Rowe, 1988; McCarthy, 2007). In recent years, the emergence of age-appropriate hardware and software has enabled educators to improve the learning process for younger learners. These tools have included a variety of teaching tools that range from tangible resources (e.g., Lego robots, sensors) to digital resources (e.g., block-programming platforms, web-based simulation tools, games) (e.g., McGovern & Fager, 2007; Sakulkueakulsuk et al., 2018). For example, Google's Teachable Machine and Machine Learning for Kids both allow students to easily create machine learning models by training computers to recognise images, sounds and poses (e.g., García et al., 2006; Toivonen et al., 2020). The availability of these assistive learning tools has allowed beginners to focus on exploring, appreciating and assimilating the basic concepts of machine learning, instead of being overwhelmed by technicalities such as algorithms, programming languages and abstract user interfaces. With these learning tools, educators can help their students to connect technical solutions with real-world problems in a fun and interactive environment.

These teaching tools make a shift from technology-oriented pedagogical designs towards interdisciplinary instructional designs with low floor high ceiling activities. In the past, from 2000 to 2010, educators engaged students in software development to design games (e.g., Connect4, Sudoku, Pacman) and controlling robots to conduct specific tasks through various syntax-based programming languages. At that time, collaborative project-based learning required students to apply their technical knowledge, programming skills and practical work in computer laboratories. Students can co-create their artifacts and solve authentic problems with their classmates. Moreover, the so-called playful experimentation merely required students to design programmable games through syntax (e.g., MATLAB, Python, C++) (Ribeiro et al., 2009; Russell & Norvig, 2002), and not exactly the playful and joyful experiences (e.g., Machine Learning for Kids, AI for Ocean at Code.org) that young learners experience today (Wangenheim et al., 2021).

With appropriate teaching tools and pedagogies, AI teaching has a lower barrier to entry for young learners to create their intelligent agents and apply what they have learnt. Learning activities are no longer focusing on computer science-oriented projects that require students' prerequisite programming skills; instead, educators try to align with global trends in STEAM education and other important competencies such as communication and collaboration. With more age-appropriate teaching tools, educators can scaffold students' AI understanding through playful experiences and visualize the complex AI concepts (García et al., 2006; Toivonen et al., 2020). On top of knowing and understanding AI, students can further create their intelligent agents and machine learning models with their peers to solve authentic problems via block-based programming and intelligent agents (Estevez et al., 2019; Sakulkueakulsuk et al., 2018). Educators can incorporate STEAM-related projects in AI learning to stimulate students to apply knowledge and solve real-life problems with their peers. With a shift towards interdisciplinary instructional design, educators can motivate students to solve authentic problems in STEAM subjects (Sintov et al., 2016) and learn how to communicate and collaborate with their peers using AI (Carpio Cañada et al., 2015). This aligned with scholars in recent couple of years who proposed the use of various hands-on and interactive activities (e.g., project-based learning, collaborative learning, learning with games) in AI literacy education to leverage students' interests and engagement and enhance their awareness of AI ethical issues (Van Brummelen et al., 2021; Lin et al., 2021). In the future, AI developers and educators should work together to design meaningful age-appropriate teaching tools and pedagogies. In this way, they can reinforce students' AI concepts using emerging tools that do not require much prerequisite knowledge, and foster their learning outcomes through engaging pedagogies.

6.3 Recommendations for AI educators

Technological innovations have played a prominent role in transforming how educators teach AI. Teaching aids have been made available to enrich students' learning experiences, develop communication, make learning engaging, and support interactive learning. This section suggests a set of recommendations for educators.

- Although students may have experience using AI technologies before, they may not know the knowledge and ethical concerns behind. As long as AI is influencing people's everyday life, it is proposed that AI literacy could be one of the important twenty-first century technological skills that students should learn to facilitate their learning and living.
- With government policy and funding support, schools could upgrade related infrastructure and teaching equipment (e.g., robotics, intelligent agents, chatbots) to offer a smart learning environment.
- Educators should update their technological knowledge such as machine learning, natural language processing, and software development to teach their students AI knowledge and skills. More professional development programs and school support are required to upskill and reskill teachers' knowledge and skills.
- Educators in primary and secondary schools may not have the computer science knowledge background to design AI curricula. They should collaborate with other stakeholders (e.g., technology companies, universities) to design meaningful AI learning projects and activities.
- With meaningful curricula, educators need to consider suitable teaching tools and pedagogies to fulfill students' needs, and use engaging elements such as game elements, curiosity, creativity, authenticity, collaboration and competition. Teachers should use age-appropriate tools such as machine learning model trainers and block-based programming that could facilitate students to visualize theories, apply what they have learnt to co-build their intelligent agents and solve authentic problems via project-based learning (Toivonen et al., 2020).
- More curriculum guides and frameworks are developed to support educators to start their AITL. Educators are advised to review their STEM-related curricula and provide students with diversified learning resources and teaching practices.
- Educational researchers and practitioners can design suitable assessment methods (e.g., surveys, questionnaires, interview protocols) to examine students' learning outcomes using AI technologies.
- Few frameworks (e.g., AIK12, 2019; Long & Magerko, 2020) were identified in this study to propose key ideas and design considerations of AI literacy education that give educators a bird's eye view of instructional design to align goals and design learning activities, teaching materials, assessments and pedagogies.

After all, it is foreseen that more research studies and works related to instructional and theoretical frameworks, and practical implementation are needed in order to understand effective practices of AITL.

7 Conclusion

In this paper, a systematic review was conducted for AITL empirical research over the past two decades. Learner types, teaching tools and pedagogical approaches were examined. The results show supporting evidence why teaching AI was not popular in primary and secondary education in the past before 2021. Most of the

AI courses/interventions focused on university computer science education. Until more age-appropriate teaching tools are developed, teaching AI started to emerge in K-12 classrooms to scaffold learners' AI understandings. Since then, AI literacy has quickly become integral parts of the twenty-first century skills (Ng et al., 2022a). On top of gaining AI knowledge and skills in using AI tools, educators can develop students' digital competencies that enable them to communicate and collaborate with AI. Countries across the globe are developing strategic initiatives and educational standards to equip students with the skills and knowledge needed to live and work in today's digital world (Touretzky et al., 2019).

However, there is no existing review summarizing how AITL research looks like to provide the research basis for AI literacy education. The lessons learnt, especially pedagogical considerations, from this review are valuable for educators to inform them how to develop AI literacy education nowadays. Through content and thematic analysis, it is found that most of the past studies used collaborative projects and game elements to engage students in problem-solving, tinkering with artifacts such as intelligent agents and robots. Among these activities, robotics, software development and interacting with intelligent agents are the most common learning tools that help students develop AI understandings. Several challenges were identified which made past educators difficult to teach AI in their classrooms: providing cognitive scaffoldings and understanding syntax for novice programmers, and building teachers' AI confidence and digital competence. The research evidence from this review addresses the importance of AI literacy and AI ethics education. Overall, it provides a research basis to inform educators how to design pedagogical strategies and use appropriate teaching tools to better prepare students to become responsible AI literates for today's digital world.

This review has several limitations. First, this review may limit the scope of the literature examined since some studies may use broader terms such as software development or robotics design without mentioning AI. One possible reason is that researchers have a controversy between hard and soft AI that some may not consider rule-based intelligence as having the AI abilities to learn, think and process. These studies would be missed and excluded due to definition arguments. Future research could more thoroughly search for additional AI technologies and broader terms to discover more AITL literature. Second, as AITL is an emerging field, the majority of the articles reviewed are conference papers listed by the Scientific Journal Rankings index (in publications such as the *ACM SIGCSE Bulletin* or *IEEE Access*). After 2020, more studies documented treatment and control groups, and used varied data analysis procedures (e.g., structural equation modeling, t-test and ANOVA) (e.g., Chiu et al., 2021; Xia et al., 2022). In the future, we foresee that researchers will conduct more rigorous evidence-based research using quantitative and qualitative methods to critically examine the effectiveness of AI curricula. Lastly, there is insufficient research before 2021 to support the development of theoretical frameworks for the teaching and learning of AI. To advance the field of AITL, recent researchers have started to develop more theoretical frameworks (e.g., AIK12, 2019; Long & Magerko, 2020) to guide educators in creating lesson designs that offer the most appropriate pedagogies and teaching tools for each AI training goal.

Appendix 1

Table 5 Lists of selected articles from Web of Science and Scopus databases (2000–2020)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
1	Mota-Valtierra et al. (2019)	Sustainability	CS-major undergraduates	Mexico	347	3 years	Exploratory qualitative study (curriculum analysis)
2	Popescu & Badica (2011)	International Journal of Information Systems and Social Change	CS-major undergraduates, teachers	Romania	42	Not specified	Mixed methods (score, opinion survey, questionnaire, observation, learning artifacts)
3	Wallace et al. (2010)	Computer Science Education	All undergraduates	Canada	25	2.5 months	Mixed methods (survey, observation, observation, learning artifacts)
4	Carpio Cañada et al. (2015)	Journal of Computer Assisted Learning	CS-major undergraduates,	Spain	83	2 months	Quantitative results (survey, score)
5	Fernandes (2016)	Computer Applications in Engineering Education	CS-major undergraduates,	Brazil	60	9 months	Quantitative results (survey, score)
6	Chiu & Chai (2020)	Sustainability	Secondary school teachers	Hong Kong	Not specified	2 months	Qualitative methods (interview, curriculum analysis)
7	Klassner (2002)	Computer Science Education	CS-major undergraduates,	USA	Not specified	1 month	Qualitative methods (opinion survey, observation)
8	Hill & Alford (2004)	ACM SIGCSE Bulletin	CS-major undergraduates,	USA	21	Not specified	Exploratory qualitative study

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
9	McGovern & Fager (2007)	Proceedings of the 38th SIGCSE technical symposium on Computer science education	CS-major undergraduates	USA	80	3 months	Mixed methods (questionnaire, interview, observation, learning artifacts)
10	Imberman (2004)	Journal on Educational Resources in Computing	CS-major undergraduates	USA	37	3 months	Qualitative methods (interview, observation, learning artifacts)
11	Estevez et al. (2019)	IEEE Access	Secondary students	Spain	Not specified	Not specified	Mixed methods (questionnaire, open-ended questions, observation, learning artifacts)
12	Straub et al. (2017)	IEEE Electro Information Technology Conference	CS-major undergraduates	USA	172	3 months	Quantitative results (survey, score)
13	Silapachote & Srisuphab (2014)	IEEE Global Engineering Education Conference	CS-major undergraduates, teachers	Thailand	202	3 months	Quantitative results (survey, score)
14	Albu (2012)	IEEE Frontiers in Education Conference	CS-major undergraduates	Canada	Not specified	2.5 months	Not specified
15	Pantic et al. (2005)	IEEE Transactions on Education	CS-major undergraduates	UK	100	Not specified	Mixed methods (grades, questionnaire, interview, observation, learning artifacts)
16	McKee (2002)	IEEE International Conference on Robotics and Automation	CS-major undergraduates	UK	Not specified	2 months	Mixed methods (feedback questionnaire, behavioral analysis in learning platform, observation, learning artifacts)

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
17	Imberman (2005)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not specified	1 month	Qualitative methods (students' reactions, observation, learning artifacts)
18	Sánchez-Nielsen & Klink (2011)	ACM Innovation and Technology in Computer Science Education	CS-major undergraduates	Spain	Not specified	2 months	Exploratory qualitative study
19	Chiang (2007)	IEEE International Workshop on Digital Game and Intelligent Toy Enhanced Learning	CS-major undergraduates	Taiwan	Not specified	Not specified	Qualitative methods (interview, observation, learning artifacts)
20	Kumar et al. (2006)	ACM SIGCSE Bulletin	CS-major undergraduates	USA	Not specified	Not specified	Exploratory qualitative study
21	Scheessele & Schriefer (2006)	ACM SIGCSE Bulletin	CS-major undergraduates	USA	16	3 months	Mixed methods (survey, questionnaire, interview, observation)
22	Hartness (2004)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not specified	Not specified	Exploratory qualitative study
23	Weidong et al. (2009)	IEEE International Conference on Computer Science and Education	CS-major undergraduates	China	Not specified	2 months	Qualitative methods (interview, observation, presentation)
24	Ribeiro et al., (2009)	Informatics in Education	CS-major undergraduates	Portugal	37 respondents	2 months	Quantitative results (survey, score)
25	Wong et al. (2010)	Proceeding of the Engineering Applications of Artificial Intelligence Symposium	CS-major undergraduates	USA	Not specified	Not specified	Exploratory qualitative study

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
26	DeNero and Klein (2010)	AAAI Symposium on Educational Advances in Artificial Intelligence	CS-major undergraduates, graduate students	USA	Not specified	Not specified	Exploratory qualitative study
27	McGovern et al., (2011)	AAAI Symposium on Educational Advances in Artificial Intelligence	CS-major undergraduates	USA	Not specified	3 months	Not specified
28	Kumar (2001)	IEEE Frontiers in Education Conference	CS-major undergraduates	USA	Not specified	3 months	Exploratory qualitative study
29	Wolfer (2019)	IEEE Experiment International Conference	CS-major undergraduates	USA	Not specified	Not specified	Exploratory qualitative study
30	Merzbacher (2001)	ACM SIGCSE Bulletin	All undergraduates	USA	14	3.5 months	Qualitative methods (students reactions, feedback)
31	Dodds (2008)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not ssecondarpecified	Not specified	Mixed methods (score, survey, questionnaire, observation, learning artifacts)
32	Cicirello (2008)	Journal of Computing Sciences in Colleges	All undergraduates	USA	32	Not specified	Exploratory qualitative study (curriculum analysis)
33	Swoboda et al. (2011)	ACM Technical Symposium on Computer Science Education	CS-major undergraduates	Spain	Not specified	3 months	Exploratory qualitative study
34	Sabuncuoglu (2020)	ACM Conference on Innovation and Technology in Computer Science Education	Secondary students	Norway	60 students, 18 teachers	9 months	Exploratory qualitative study (curriculum analysis)

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
35	Michaud (2014)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not specified	1.5 months	Mixed methods (survey, questionnaire, interview, observation)
36	League (2008)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not specified	3.5 months	Exploratory qualitative study
37	Kozak (2006)	Journal of Computing Sciences in Colleges	CS-major undergraduates	USA	Not specified	Not specified	Exploratory qualitative study
38	Bryce (2011)	Journal of Computing Sciences in Colleges	CS-major undergraduates, graduate students	USA	Not specified	2 months	Exploratory qualitative study
39	Narahara & Kobayashi (2018)	ACM SIGGRAPH Conference	Primary and secondary students, all undergraduates	USA	Not specified	Not specified	Exploratory qualitative study
40	Toivonen et al. (2020)	IEEE International Conference on Advanced Learning Techn	Primary students	Finland	34	Not specified	Qualitative methods (interview, observation, learning artifacts)
41	Chai et al. (2020)	IEEE International Symposium on Educational Technology	Primary students	Hong Kong	131	Not specified	Quantitative methods (questionnaire)
42	Sintov et al. (2016)	AAAI Conference on Artificial Intelligence	Secondary students, all undergraduates	USA	30 secondary students, 30 university students, 28 adult learners	0.5 months	Quantitative methods (questionnaire)
43	Goel & Joyner (2017)	AI Magazine	Graduate students	USA	2000 +	Not specified	Quantitative methods (questionnaire)

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
44	García et al. (2006)	IEEE International Symposium on Computers in Education	Primary students	Spain	Not specified	Not specified	Exploratory qualitative study
45	Kandlhofer et al. (2019)	IEEE Frontiers in Education Conference	Secondary students	Austria	Not specified	Not specified	Exploratory qualitative study
46	Li et al. (2014)	IEEE Frontiers in Education Conference	CS-major undergraduates	Australia	Not specified	3 months	Exploratory qualitative study
47	Barik et al. (2003)	IEEE Frontiers in Education Conference	CS-major undergraduates	USA	14	4 months	Mixed methods (survey, questionnaire, observation, interview)
48	Sakulkueakulsuk et al. (2018)	IEEE International Conference on Teaching, Assessment, and Learning for Engineering	Secondary students	Thailand	84	3 days	Mixed methods (survey, questionnaire, observation, learning artifacts)
49	García et al. (2006)	IEEE Frontiers in Education Conference	CS-major undergraduates	Spain	108	Not specified	Mixed methods (score, opinion survey, questionnaire, observation)
50	Van Brummelen et al. (2021)	AAAI Conference on Artificial Intelligence	Secondary students (8-12th grade)	UK	47	2 weeks	Mixed methods (knowledge gain, digital competency, student projects)
51	Lin et al. (2021)	Educational Technology & Society	Non-engineering undergraduates	Taiwan	328	3 weeks	Mixed methods (questionnaire)
52	Zammit et al. (2021)	Proceedings of the European Conference on Games-Based Learning	Primary and secondary students	Matla	22	Not specified	Exploratory qualitative study

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
53	Xu and Babaian (2021)	International Journal of Management Education	Business undergraduates	USA	16	15 weeks	Mixed methods (student perception questionnaire, interview)
54	Allen et al. (2021)	ACM Transactions on Computing Education	Computer science, mathematics, digital health, management and finance	USA	50	Not specified	Mixed methods (semi-structured interviews, questionnaires, one-minute paper, observation)
55	Chen et al. (2022)	Decision Sciences Journal of Innovative Education	Management information systems	USA	85	12 weeks	Mixed methods (pre-post tests, interviews)
56	Wood et al. (2021)	Journal of Medical Education and Curricular Development	Medical students	USA	121	Not specified	Quantitative (pre-post survey)
57	Polpanumas et al. (2021)	IEEE International Conference on Engineering Technology and Education	Middle/high school students	Thailand	25	3 weeks	Mixed methods (projects, post-survey)
58	Zeng and Xie (2021)	AAAI Conference on Artificial Intelligence	Engineering	USA	292	15 weeks	Qualitative (survey, observation)
59		AAAI Conference on Artificial Intelligence	Primary and secondary students	Germany	24	3 sessions	Quantitative (post-test)
60	Greenwald et al. (2021)	AAAI Conference on Artificial Intelligence	High school students	USA	8	Not specified	Qualitative (interview)
61	Chiu et al. (2021)	IEEE Transactions on Education	Secondary students	Hong Kong	335	12 chapters	Mixed (pre-post questionnaire, interview)

Table 5 (continued)

	Author(s) and year	Journal	Learner type(s)	Region(s)	Sample size (n)	Study duration	Method(s)
62	Chai et al. (2021)	Educational Technology & Society	Primary students	Hong Kong	682	6 h	Quantitative (questionnaire)
63	Chang and Tsai (2021)	Educational Studies	High school students	Taiwan	65 experimental group; 37 control group	Not specified	Mixed (questionnaire, interview, drawing, cloud diagram)
64	Ng and Chu (2021)	Online learning	Secondary students	Hong Kong	98	3 weeks	Mixed (questionnaire, interview)
65	Long et al. (2021a)	Proceedings of the ACM on Human–Computer Interaction	Primary students	USA	11	2 days	Qualitative (interview)
66	Kim et al. (2021)	AAAI Conference on Artificial Intelligence	Primary students	Korea	60	8 weeks	Quantitative (survey)
67	Voulgari et al. (2021)	ACM Interaction design and children	Primary and secondary students	Greece	130	Not specified	Mixed (questionnaire, interview)
68	Lee et al. (2021)	ACM Technical Symposium on Computer Science Education	Secondary students	USA	Not specified	10 weeks	Qualitative (interview)
69	Baldoni et al. (2023)	Psychology-Based Technologies, Psychobit	Primary students	Italy	200	12 weeks	Quantitative (survey)
70	Druga et al. (2019)	ACM Interaction design and children	Primary students	USA	52	4 weeks	Qualitative (interview)
71	Henry et al. (2021)	Artificial Intelligence	Secondary students, primary students	Belgium	70 secondary students, 12 primary students	Not specified	Qualitative (interview, verbal assessment)
72	Long et al. (2021b)	ACM Creativity and Cognition	Primary students	USA	21	Not specified	Mixed (Survey, interview)

Appendix 2

Table 6 Literature summary of AITL studies

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
1	Mota-Valtierra et al. (2019)	To evaluate an AI course in four years to identify how students develop practical knowledge about AI based on constructivism	Neural network, finite impulse response, wavelet transform, empirical mode decomposition, multilayer perceptron	Collaborative learning, project-based learning, real-world problem solving	Matlab programming	• The study showed that students obtained an increase in the average of the grades and the perception throughout the practical sessions
2	Popescu & Badica (2011)	To illustrate the use of the Web-based Educational Learning Style Adaptive System in a personalized AI course which was individualized to the learning style of students	Searching (e.g., Breadth-first search)	Personalized learning, online learning	Adaptive learning system	• The study showed that the personalized AI course using an adaptive learning system can effectively engage students in the learning content • Students appreciated the course content, presentation, platform interface, navigation options and communication tools • They perceived a large degree of concordance between the course and the matched self diagnosed learning preferences, and the usefulness of the adaptation process • The three teachers taught in the course felt satisfied with their teaching experience with the WELSA course platform
3	Wallace et al. (2010)	To examine the use of game-based laboratory projects (e.g., robot defense, checkers) to learn AI concepts	Dijkstra's algorithm, A* search, Q-Learning to create an agent, machine learning	Collaborative learning, project-based learning, serious game elements (robot defense game)	Web-based games (e.g., robot defense, checkers)	• Instructor observed that students enjoyed and engaged with the game-based projects • Surveys indicated a stronger perception of learning and interest from students compared with students who use non-game based projects in a series of indicators (teacher/student interaction, perceived ability, interest, motivation, learning experience)

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
4	Carpio Cañada et al. (2015)	To investigate how students enhance AI understanding and motivation, interest and personal skills in an international online competition through play	Evolutionary algorithms, fuzzy logic, neural networks	Collaborative learning, project-based learning, real-world problem solving, online competition	Online competition with virtual robots	• The computer-based competition consolidated students' AI concepts, improved their learning perception on courses, motivation and interest, and broadened personal skills (cooperation, teamwork, organization, value of information sharing) • Additional teaching goals (learning new programming languages, increasing course attendance) were obtained because of the positive motivation experienced throughout the competition
5	Fernandes (2016)	To reveal the effect of problem-based learning in an AI course, in which students develop solutions to enable the collision-free movement of a wheeled robot in unknown simulated environments	Neural network, binary logic with Prolog, fuzzy logic, genetic algorithms	Collaborative learning, project-based learning, real-world problem solving	Collision-free virtual robots	• More than 80% responses were positive in different affective and cognitive aspects (perceptions towards problem-based learning, learning satisfaction, perceived ability, preference of working in pairs)

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
6	Chiu & Chai (2020)	To explore the views of teachers with and without AI teaching experience on key considerations for the design, implementation and revision in a K-12 AI curriculum in a five-stage curriculum development cycle (i.e., preparation, content design, process design, design and development, reinforcement)	Not specified	Not specified	Not specified	• Perceived needs: AI curriculum was needed for preparing school students to learn about the emerging AI technologies • Professional development activities: Teachers perceived a strong need to earn AI knowledge and curriculum design capacity from different experts • Multilevel engagement: It was crucial to engage school leaders, teachers, university professors and industrial partners in the curriculum developmental process • Curriculum design: Teachers expressed that the content and product in AI lesson planning should be an integrated approach in a multi-disciplinary nature, instead of an independent subject • The major components of AI curriculum were knowledge in, process in, and impact of AI, which should be taught in a familiar language (e.g. graphic representations) to explain the related technologies, knowledge and concepts, and prevent cognitive load • Learning activities were designed to help students to understand and aware AI via experiential connection, student-centered learning (e.g. PBL, design thinking) and ethical concerns about AI • Teachers should give examples of real-world applications which must be relevant to students in a local context and connect subject knowledge to their own experiences (e.g. KKBox, Spotify)

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
8	Hill & Alford (2004)	To present a case study to realize a distributed configurable task environment via agent-based software	Intelligent agent (searching, logical agent)	Collaborative learning, project-based learning, serious game elements (Wumpus world game)	Lego robots	• The case study showed that students gain a fuller understanding of AI concepts by implementing agents that embody intelligent behavior • Students knew how to program in different languages and have different levels of programming abilities. Also, they could incorporate advanced capabilities into their agents through a configurable task environment
9	McGovern & Fager (2007)	To evaluate the effectiveness of an arcade-style gaming environment in terms of student evaluations, comments and exam grades	A* search, reinforcement learning	Collaborative learning, project-based learning, serious game elements (Spacewar), real-world problem solving	Robots making, sensors	• Students enjoyed the project and fulfilled the criteria of a successful project (e.g. extensive so that stronger students can explore alternatives to the main solution approach) • The AI learning course stimulated students' interest and helped them apply AI principles and techniques
10	Imberman (2004)	To propose an intelligent agent approach to teach neural networks and back propagation with the use of Lego and video game programming	Neural network, back propagation, machine learning	Collaborative learning, project-based learning, real-world problem solving	Spacewar simulation games, Lego robots, board games	• Students could realize the difference between training a neural network and the trained neural network. Interesting elements (e.g., video game programming, intelligent agents) encouraged students to elect AI as part of their course of study
11	Estevez et al. (2019)	To represent hands-on workshops to pedagogically scaffold to learn AI through construction and experimentation of intelligent systems	K-means algorithm (unsupervised learning), neural network, impact of AI in everyday life	Collaborative learning, project-based learning	Lego robots	• Scratch programming could introduce students to AI fundamentals and enhance their awareness of AI, technical knowledge such as using algorithms to predict the result of some real-life applications (e.g. football match)

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
12	Straub et al. (2017)	To explore the correlations between different characteristics, efficacy and performance in an introductory AI course	Not specified	Not specified	Scratch blockly-based programming	• The study identified student characteristics which correlated with perceived effectiveness in class activities, efficacy and expected performance
13	Silapachote & Srisuphab (2014)	To examine the reflections of the AI course in terms of students' attention and pedagogies in programming tasks	State presentations, uniformed/ blind search, informed search, minmax game trees, and alpha–beta pruning routine	Collaborative learning, project-based learning, game elements, real-world problem solving	Programming	• The AI competitive elements into cooperative activities significantly lengthened students' short attention span and give a positive feedback on pedagogies (e.g. learning-by-doing, cooperative learning, repetitive exercises)
14	Albu (2012)	To evaluate the AI learning experience via video-based online learning with respect to traditional learning	Machine learning, computer vision, games, robotics, natural language processing	Video-based learning, online learning	Puzzle board, grid game, Ataax games	• The overall student performance in the AI class scored at slightly less than 90% which was higher than traditional learning • Immediate experimentation with AI concepts via quizzes was engaging. The informal and low-tech aspect videos added an interesting social dimension to the AI course
15	Pantic et al. (2005)	To implement a flexible method of teaching introductory AI using a novel Java-implemented simple agent framework	Rule-based reasoning, semantic networks/ agent-based system	Collaborative learning, project-based learning, real-world problem solving	Quiz-like video clips, Java-based simple agents	• The results indicated the use of a Java-based simple agent framework could be an effective way of teaching introductory AI. In turn, the system and the specified AI programming projects were useful • Students found that developed educational tools and the programming assignments were motivating to learn the basics of AI

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
16	McKee (2002)	To present the learning context of network-based robotics projects to understand infrastructure support for internet-based robotics projects and online robot demonstrations	Searching	Collaborative learning, project-based learning, real-world problem solving	Java-based agents	• The results demonstrated a pattern of usage that reflects learning progression and exponential increase in usage of facilities as the project deadline approaches
17	Imberman (2005)	To describe three case studies with a series of AI learning activities (chatbots with turing test, heuristics in a puzzle problem and neural network with Lego robot)	Turing test, puzzle problem, Lego robot	Project-based learning	Web-based (virtual and physical) robots	• The case study presented three projects which received positive feedback from students
18	Sánchez-Nielsen & Klink (2011)	To present the use of Google developer toolkits in AI courses for students to learn AI concepts on academic topics and build value-added applications in real world projects	Searching strategies, multiagent system, software development	Collaborative learning, project-based learning, real-world problem solving	Google developer toolkits	• The students could focus on the use of academic topics to build value-added applications in real world projects • The use of Google developers toolkits allowed students to acquire AI knowledge via hands-on experience, appreciate the interplay between theory and practice, development of real-world software projects, and promoted teamwork and cooperative learning
19	Chiang (2007)	To report adapting traditional Pacman games with machine learning technology with case-based reasoning to motivate students in AI learning	Machine learning, neural network, A* search, case-based reasoning agent	Project-based learning, game elements	Pacman, spacewar simulation games	• The study found that the fun of interactive computer games would stimulate students' motivation in learning AI concepts
20	Kumar et al. (2006)	To present three approaches for making AI projects through machine learning around a central theme, inexpensive roots as the platform and software platforms	Python robotics, machine learning, N-puzzle problem, classification	Project-based learning, game elements, real-world problem solving	Lego robots, Python programming	• Students were better motivated to learn the fundamental concepts of both AI and machine learning • The projects stimulated students' interest in learning AI and machine learning

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
21	Scheessele & Schriefer (2006)	To propose an flexible, authentic and feasible introductory AI course that assigns poker-playing agents as a group project	Rule-based system, game agents, machine learning	Collaborative learning, project-based learning, game elements, real-world problem solving	Poker-playing agents	• Students enjoyed the project based on survey and instructor observations. Each team developed their own poker agents which were stronger than random agents
22	Hartness (2004)	To describe a game called Robocode that allows students to develop Java-based virtual gamified robots	Game tree search, genetic algorithm, reinforcement learning	Game elements	Robocode games	• By incorporating an enjoyable game into an artificial intelligence class and providing students with tools for developing practical versions of the algorithms discussed in class, the students were encouraged to master difficult AI concepts and better appreciate the theory and develop greater confidence in their understanding of it
23	Weidong et al. (2009)	To summarize the development and necessity of research-based teaching to learn AI	Not specified	Collaborative learning, project-based learning	Not specified	• The case study demonstrated the development and necessity of research-based teaching, and discussed the process and problems during implementation in an AI course • Compared with conventional teaching, research-based teaching was an effective pedagogy to stimulate student interest
24	Ribeiro et al., (2009)	To describe an experience in the context of undergraduate teaching of AI to motivate students on the deepening of the topics	Prolog programming	Collaborative learning, game elements	Puzzle board, grid game, Matlab	• The paper reported the impact of competitive learning to deepen student AI concepts, foster student active participation, and increase learning motivation to improve students' learning experience

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
25	Wong et al. (2010)	To develop projects about AI topics that use video-game technology and Pinball machines to motivate students to learn AI concepts	Trajectory replanning, path planning, gesture recognition with neural network	Project-based learning, game elements	Pinball machine (physical robot), video games	• The study presented a teaching case study where we used two projects as games as motivators. First, computer games developed projects on AI topics that used video-game technology to motivate the students' learning • The Pinball project encouraged students to develop hardware and software to apply AI concepts to develop games on actual machines
26	DeNero and Klein (2010)	To propose a Pacman game in four projects which encourage students to implement AI concepts	State-space search, multi-agent search, reinforcement learning, probabilistic learning, interactive multi-agent	Collaborative learning, project-based learning, game elements	Pacman games	• The Pacman projects focused on learning AI topics which have been effective in motivating students and creating opportunities to apply general techniques they have learnt in lectures
27	McGovern et al., (2011)	To introduce a Java graphical gaming framework to enable students to learn AI to apply and visualize the topics from the class	A* search	Collaborative learning, project-based learning, game elements, real-world problem solving	Puzzle board, grid games, Pacman, spacewar simulation games	• The Java games were very effective tools in enabling students to easily apply AI algorithms to new domains, and improving their examination performance. They gained more practical experience in designing algorithms and software products via team-based projects
28	Kumar (2001)	To report experience using robots in an AI course in which we use robots to reinforce AI concepts	Binary tree, heuristic search, rule-based expert system	Collaborative learning, project-based learning	Lego robots, expert systems	• The study found that using Lego robots was an effective tool for students to learn more interestingly, and be more engaged • It also engaged students to help them to learn AI concepts better and offer them opportunities to apply and implement AI concepts

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
29	Wolfer (2019)	To embed a biomedical motif in an AI course to learn related techniques and principles	Using AI to augment medical image processing, classifying arterial plaque (classification, image recognition)	Collaborative learning, project-based learning, real-world problem solving	Biomedical applications	• The study reviewed the advantages and disadvantages when embedding a biomedical motif in an AI course. The result showed that students could use AI to solve real-world biomedical problems • Over-contextualization should also be paid attention so that students can explore areas beyond the course motif
30	Merzbacher (2001)	To evaluate a one-credit AI course for non-computer science students with the use of hands-on exercise and software demonstrations to illustrate the principles of AI	Searching, expert system, natural language, neural network, genetic algorithm	Collaborative learning, project-based learning, game elements, real-world problem solving	Not specified	• The study presented various technical topics in AI, ranging from expert systems to neural networks, without requiring any programming or mathematics background. The course used a mixture of hands-on exercises and software demonstrations to illustrate the principles behind AI • Despite the technical subject matter, students from a variety of majors reported that they found the course both accessible and interesting
31	Dodds (2008)	To present low (robotics programming via simulated and real platforms, audio processing and classification), and high-level AI-themed activities (automated game-playing and reasoning about language) to learn AI concepts	Recursion and reasoning, Natural language, Audio classification, Robot programming	Game elements	Connect4 games	• The study demonstrated appropriate scaffolding to motivate students to learn AI topics via four AI-themed assignments (i.e. game-playing, text processing, audio classification, and robot programming)
32	Cicirello (2008)	To introduce a course that provides an overview of diverse fields including computer science, philosophy, psychology and economics	Philosophy (e.g., philosophy of mind, logic, and rationality), psychology (e.g., nature of intelligence), economics (game theory)	Collaborative learning, real-world problem solving	Not specified	• The study showed that the non-Computer Science undergraduates could learn the fundamental AI elements in the liberal arts curriculum

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
33	Swoboda et al. (2011)	To describe a collection of course materials designed to be used in an introductory AI course with robot simulator and real robots	Advanced search (e.g. heuristics, genetic algorithm), machine learning, (e.g. neural networks), robotics (e.g. sensing, world models, planning, programming, navigation, etc.)	Collaborative learning, project-based learning, real-world problem solving	Robot simulator and real robots	• The study showed that using robot simulators and real robots could satisfy students' learning expectations, motivate them to learn and produce high quality work
34	Sabuncuoglu (2020)	To design an AI curriculum for middle schools based on Touretzky's "Five Big Ideas on AI Education"	Learning from dataset, image and voice recognition (e.g., pixel and algorithms, classification with frequency), human–computer interaction, societal and ethical aspects	Project-based learning, game elements	Interactive reading, pixel matching, image filter, color detection, online applications of computer vision, rock-paper-scissors with Google Teachable Machine	• The study suggested that exploring digital content with physical tasks could promise an interesting design space for students to gain their skills to choose appropriate sensors to solve a problem, build an algorithm, find a valid data set to structure an AI model, and design interactions to make the interface more human-friendly and ethically
35	Michaud (2014)	To address the social, cultural and ethical perspectives in the field of AI regarding robotics design	Societal, cultural and ethical aspects	Project-based learning	Robots	• The study illustrated that students could achieve desirable outcomes in terms of a deeper understanding of the impact of computer discipline in their society. Nearly 90% of students reported that the robotic projects could help them understand the societal, cultural and ethical context
36	League (2008)	To design AI lab assignments that span learning styles and aptitudes for all undergraduate students	Turing test, Strong/weak AI, Agent, Machine learning, Heuristic search, Advanced search, Knowledge representation, logic, expert system	Project-based learning, game elements	Puzzle board, grid games, Connect4, Sudoku games	• The study presented a set of workbook-style lab assignments (interactive lecture notes and software demonstrations) with questions, tasks and projects. It was found that the instructional design aligned with Bloom's taxonomy, and spanned students' learning styles and aptitudes

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
37	Kozak (2006)	To describe a web-based shell interface that provides the student insight into how AI algorithms can be embedded in broader applications	Strong/weak AI, backward chaining, rule selection, minimax trees, heuristic searches, probabilistic reasoning, decision trees, and Bayesian methods	Collaborative learning, project-based learning, real-world problem solving	Avatar movement, tile-based games	• The study described the use of web-based applications and games to illustrate how and why AI algorithms were embedded in broader applications (e.g. client management system, inventory system) via AI techniques such as backward and forward chaining, and semantic modelling
38	Bryce (2011)	To present an overview of an introductory AI course that uses five projects based on the game of Wumpus World	Search, heuristic search, propositional logic, knowledge representation, probabilistic inference queries (e.g. bayesian network)	Project-based learning, game elements	Pacman, Wumpus World games	• The study presented a fun and simple software framework in the Wumpus World projects that stimulated students to reflect on why different AI approaches work
39	Narahara & Kobayashi (2018)	To introduce AI and robotics to beginners of all ages in STEAM fields via three steps (playing and testing in the VR environment, training an AI model based on dataset acquired from the virtual testing, running a toy car using a trained AI model on a physical track)	Convolutional neural network, image recognition	Project-based learning, game elements, real-world problem solving	Toy virtual and physical car	• The study tested a proposed framework for AI learning by combining AI and robotics together in an AI driving package with a toy robotic car
40	Toivonen et al. (2020)	To investigate how to use Google Teachable Machine for teaching ML principles in primary schools, and what technical and pedagogical issues should be considered when designing ML teaching interventions	Convolutional neural networks, machine learning	Collaborative learning, project-based learning, real-world problem solving	Google Teachable Machine	• The results show that Google Teachable Machine was well suited for teaching ML principles even for younger primary school kids, and when designing ML interventions with Google Teachable Machine, one has to make sure that students have the time and resources for collecting large enough and rich enough sets of training data for the models. Google Teachable Machine was a feasible and mature tool for average users with limited or no previous experience on programming or related subjects

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
41	Chai et al. (2020)	To conduct an exploratory factor analysis to examine students' AI literacy, confidence in AI, and AI for social good and behavioral intention	AI literacy, confidence in AI, AI for social good	Project-based learning, real-world problem solving	Not specified	• The results addressed how students' confidence, AI literacy, AI for social good were positively associated with their behavioral intention. The three elements could successfully predict their behavioral intention
42	Sintov et al. (2016)	To evaluate the use of a game-based research platform to teach AI and game-based theories via role-playing games	Game-theory based algorithm, machine learning	Collaborative learning, project-based learning, game elements, real-world problem solving, role-playing	Role-playing board games	• The results showed that a game-based research platform was an effective approach to teach general AI and game theoretic concepts to secondary school, university and adult learners. Participants rated the learning experiences in this role-playing approach high which was engaging and broadly accessible to enhance their interest in learning AI
43	Goel & Joyner (2017)	To present the design, delivery, and evaluation of the AI online course, focusing on the use of AI for teaching AI via intelligent tutors	Semantic networks, production systems, case-based reasoning, incremental concept learning, classification, etc	Collaborative learning, game elements, real-world problem solving	Intelligent tutors	• This paper found that delivering the AI online course could satisfy the learning experiences of our careers, and encourage students to participate in this new environment. The level of student motivation, engagement and ownership were enhanced
44	García et al. (2006)	To examine the use Scratch and Machine learning for kids to develop basic M.L concepts	Machine learning	Collaborative learning, project-based learning, real-world problem solving	Machine learning for kids, Scratch blockly-based programming	• This article presented an activity design which aimed to serve as teacher inspiration and revealed four fundamental concepts of ML model, training dataset, learning and confidence

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
45	Kandlhofer et al. (2019)	To evaluate robotics projects which offer a training and certification system for trainers (teachers) and trainees (secondary school students, young people)	AI definitions and applications of AI in daily life, identifying and recognizing AI systems, fundamental data structures in AI (graph, stack, queue), basics of propositional logic and Python programming, principles and applications of natural language processing, computer vision and machine learning, solving problems by search	Project-based learning	Lego robots, robotic arms, mobile robots	• This innovative approach was a widely recognized training and certification system for teaching principles of AI and Robotics at K-12 level (complex topics adapted and prepared for both beginners and more experienced people) and fostered AI/Robotics literacy
46	Li et al. (2014)	To present serious game projects to encourage students to learn AI knowledge and computational thinking	Computational thinking (Abstraction, encapsulation, class hierarchies, composition, polymorphism), AI knowledge (depth-first search, breadth-first search, genetic algorithm)	Project-based learning, game elements	Puzzle board, grid games	• The article illustrated that the Sokoban solving serious game projects to be particularly helpful and valuable for the educational activities in our school
47	Barik et al. (2003)	To evaluate a blended learning approach through games in terms of learning attitude and learning style	Python programming, movement algorithms, pathfinding, decision making, learning	Collaborative learning, project-based learning, game elements, real-world problem solving	Pygame, tile-based game	• The article showed a positive and significant increase in students in attitude within interest and professional constructs in a blended learning classroom with game programming • However, there was no significant difference between traditional and blended learning approaches in learning styles

Table 6 (continued)

	Author(s) and year	Study purposes	Content knowledge	Pedagogy	Teaching tools	Key findings
48	Sakulkueakulsuk et al. (2018)	To present an approach in STEM education at the intersection of machine learning, gamification and social context. A Four P's Creative Learning (projects, passion, play and peers) approach was used to encourage students to connect the emerging technological solutions such as AI with the pressing real-world problems in the playful environment	Machine learning (e.g., decision tree, neural network, and k-nearest Neighbor.)	Collaborative learning, project-based learning, game elements, real-world problem solving	UI-based software for machine learning, RapidMiner, Mango ML model	• The study found that machine learning can be used as a tool to successfully conduct interdisciplinary learning at the middle school level • The student came up with a higher accuracy to predict the sweetness and grades of mangoes, and constructed new machine learning models • Based on questionnaires, it was found that students had more fun, engagement, hands-on interactivity, futuristic thinking, interdisciplinary thinking, and the importance of AI in agriculture. This demonstrated that highly advanced concepts can be learnt by students if the learning environment was well designed and organized
49	García et al. (2006)	To use a collaborative project-based learning method to teach AI in three years	AI concepts (e.g., knowledge representation, formal logics, management of uncertainty, searching), applications (e.g., knowledge-based systems, agents, linguistic engineering, data mining, intelligent systems)	Collaborative learning, project-based learning	Intelligent agents, expert system, simulation, data mining	• The study showed that students could enhance their course performance (correct rates of questions, time for self-evaluation and peer-review process). Students showed positive feedback towards the collaborative project-based learning although they may meet learning challenges (e.g., anonymous peer-review, schedule rearrangement, time-consuming to study each others' work)

Appendix 3

Table 7 Teaching tools

Context	Learning tool/ artifact	Definition	Examples
Primary schools	Intelligent agents	Intelligent agents are used to help students construct knowledge and inquiry skills with the use of AI-enabled tools (Peña et al., 2005)	• Machine learning for kids (García et al., 2006); • Google's Teachable Machine (Toivonen et al., 2020)
	Platforms for software development	Block-based coding uses drag-and-drop coding, in which programmers use coding instruction "block"' to construct games or applications (Weintrop & Wilensky, 2015)	• Scratch (García et al., 2006)
	Robotics	Robotics encourages students to design components of robot anatomy, robot control and robot behaviour with AI models (Aoun, 2017)	• Robot simulators, real robots (Narahara & Kobayashi, 2018)
Secondary schools	Intelligent agents	Intelligent agents are used to help students construct knowledge and develop inquiry skills with the use of AI-enabled tools (Peña et al., 2005)	• Interactive reading, pixel matching, image filters, color detection, online applications of computer vision, rock-paper-scissors with Teachable Machine (Sabuncuoglu, 2020); • UI-based software for machine learning (Sakulkueakulsuk et al., 2018)
	Platforms for software development and programming	Block-based coding utilizes a drag-and-drop coding environment, in which programmers use coding instruction "blocks" to construct games or applications (Weintrop & Wilensky, 2015)	• Scratch (Estevez et al., 2019)
	Robotics	Robotics encourages students to design components of robot anatomy, robot control and robot behavior with AI models (Aoun, 2017)	• Robot simulators, real robots (Narahara & Kobayashi, 2018); • Lego robot (Kandlhofer et al. (2019)

Table 7 (continued)

Context	Learning tool/ artifact	Definition	Examples
Higher Education	Intelligent agents	Intelligent agents are used to help students construct knowledge and inquiry skills with the use of AI-enabled tools (Peña et al., 2005)	• Google developer kits (Sánchez-Nielsen & Klink, 2011) • MIT Media lab (Sakulkueakulsuk et al., 2018) • Google's Teachable Machine (Toivonen et al., 2020) • Machine Learning for Kids (García et al., 2006) • Interactive agents (Hill & Alford, 2004; Pantic et al., 2005) • Adaptive systems (Popescu & Badica, 2011) • Chatbots (Imberman, 2005)
	Platforms for software development and game design	Learning involves playful experimentation, trying new things, tinkering with materials and tools, testing boundaries, taking risks and iterating projects again and again (Shaw, 2000)	• Puzzle board and grid game (Imberman, 2005; League, 2008; Li et al., 2014; McGovern et al., 2011; Ribeiro et al., 2009; Silapachote & Srisuphab, 2014); • Pacman (Bryce, 2011; Chiang, 2007; DeNero & Klein, 2010; McGovern et al., 2011); • Spacewar simulator (Chiang, 2007; McGovern & Fager, 2007; McGovern et al. (2011); • Poker-playing agents (Scheessele & Schriefer, 2006); • Online competition (Carpio Cañada et al., 2015); • Connect4 (Dodds, 2008; League, 2008); • Sudoku (League, 2008); • Robocode (Hartness, 2004); • RapidMiner/ Mango ML model (Sakulkueakulsuk et al., 2018); • Wumpus World (Bryce, 2011); • Avatar movement and tile-based games (Barik et al., 2013)

Table 7 (continued)

Context	Learning tool/ artifact	Definition	Examples
	Platforms for software development and programming	Both syntax or block-based programming are involved in software development (Weintrop & Wilensky, 2015)	• Scratch (García et al., 2006); • Python-based artifacts (Kumar et al., 2006); • MATLAB (Mota-Valtierra et al., 2019)
	Robotics	Robotics encourages students to design components of robot anatomy, robot control and robot behaviour with AI models (Aoun, 2017)	• Lego robots (Imberman, 2004; Imberman, 2005; Klassner, 2002; Kumar et al., 2006; Kumar, 2001); • Real robots (Kandlhofer et al., 2019; Michaud, 2014; Narahara & Kobayashi, 2018; Swoboda et al., 2011; Wong et al., 2010) • Robot simulators (Dodds, 2008; Fernandes, 2016; McKee, 2002; Swoboda et al., 2011; Wallace et al., 2010)

Appendix 4

Table 8 Timeline of AI teaching tools

Year of first appearance	Teaching tools	Types	Sample studies
2001	Lego robot	Robots (physical)	Kumar (2001)
2002	Internet-based online robots	Robots (physical and online)	McKee (2002)
2004	Pathfinders, sensors, robots made to do specific tasks	Robots (physical)	Hill & Alford (2004)
	Robocode	Software development (game design)	Hartness (2004)
2005	Java-based agents, chatbots	Intelligent agents	Pantic et al. (2005), Imberman (2005)
	Puzzle boards / grid games	Software development (game design)	Imberman (2005)
2006	Python programming	Software development (programming)	Kumar et al. (2006)
	Poker-playing agents Avatar movement	Software development (game design)	Scheessele & Schriefer (2006) Kozak (2006)
	Expert systems, data mining	Intelligent agents	García et al. (2006)
2007	Spacewar simulations Pacman	Software development (game design)	McGovern & Fager (2007) Chiang (2007)
2008	Connect4 Sudoku	Software development (game design)	Dodds (2008) League (2008)
2009	MATLAB	Software development (programming)	Ribeiro et al. (2009)
2010	Pinball machines	Robots (physical)	Wong et al. (2010)
2011	Adaptive learning systems Google developer kits	Intelligent agents	Popescu & Badica (2011) Sánchez-Nielsen & Klink (2011)
2012	Quizzes with video clips	Web-based applications	Albu (2012)
2017	Intelligent tutors	Intelligent agents	Goel & Joyner (2017)
2018	User Interface (UI)-based software for machine learning, RapidMiner, Mango ML model	Intelligent agents	Sakulkueakulsuk et al. (2018)

Table 8 (continued)

Year of first appearance	Teaching tools	Types	Sample studies
2019	Scratch	Web-based applications	Estevez et al. (2019)
	Biomedical applications e.g., PhysioNet		Wolfer (2019)
	Machine learning for kids	Intelligent agents	García et al. (2006)
	Robotic arms	Robotics (physical)	Kandlhofer et al. (2019)
2020	Computer vision, Google's Teachable Machine	Intelligent agents	Sabuncuoglu (2020)

Data availability The authors declare that the data supporting the findings of this study are available within the article and its supplementary information files.

Declarations

Conflicts of interest The authors have no conflicts of interest to disclose. The manuscript has not been published previously and is not being simultaneously submitted elsewhere. There are no any real or potential conflicts of interest that could be seen as having an influence on the research. No reproduction of copyrighted material is evident in this manuscript hence there is no need to apply for any necessary permission.

References

AIK12. (2019). *Five Big Ideas about AI*. Retrieved from https://ai4k12.org/big-idea-1-overview/.

Albu, A. B. (2012). Learning artificial intelligence clip by clip. In *IEEE frontiers in education conference* (pp. 789–794). IEEE.

Ali, S., Payne, B. H., Williams, R., Park, H. W. & Breazeal, C. (2019). Constructionism, ethics, and creativity: Developing primary and middle school artificial intelligence education. In *International workshop on education in artificial intelligence K-12*. MIT Press.

Allen, B., McGough, A. S., & Devlin, M. (2021). Toward a framework for teaching artificial intelligence to a higher education audience. *ACM Transactions on Computing Education (TOCE), 22*(2), 1–29.

Aoun, J. E. (2017). *Robot-proof: Higher education in the age of artificial intelligence*. MIT Press.

Baldoni, M., Baroglio, C., Bucciarelli, M., Gandolfi, E., Ianì, F., Marengo, E., & Ras, I. N. (2023). Empowering AI competences in children: the first turning point. In *International Conference in Methodologies and intelligent Systems for Techhnology Enhanced Learning* (pp. 171–181). Springer.

Barik, T., Everett, M., Cardona-Rivera, R. E., Roberts, D. L., & Gehringer, E. F. (2013). A community college blended learning classroom experience through artificial intelligence in games. In *2013 IEEE Frontiers in Education Conference (FIE)* (pp. 1525–1531). IEEE.

Berk, L. E., & Winsler, A. (1995). *Scaffolding Children's Learning: Vygotsky and Early Childhood Education. NAEYC Research into Practice Series. Volume 7*. National Association for the Education of Young Children, 1509 16th Street, NW, Washington, DC 20036–1426.

Bryce, D. (2011). Wumpus World in introductory artificial intelligence. *Journal of Computing Sciences in Colleges, 27*(2), 58–65.

Carpio Cañada, J., Mateo Sanguino, T. J., Merelo Guervós, J. J., & Rivas Santos, V. M. (2015). Open classroom: Enhancing student achievement on artificial intelligence through an international online competition. *Journal of Computer Assisted Learning, 31*(1), 14–31.

Chai, C. S., Lin, P. Y., Jong, M. S. Y., Dai, Y., Chiu, T. K., & Qin, J. (2021). Perceptions of and behavioral intentions towards learning artificial intelligence in primary school students. *Educational Technology & Society, 24*(3), 89–101.

Chai, C. S., Lin, P. Y., Jong, M. S. Y., Dai, Y., Chiu, T. K. & Huang, B. (2020). Factors influencing students' behavioral intention to continue artificial intelligence learning. In *2020 international symposium on educational technology* (ISET) (pp. 147–150). IEEE.

Chang, Y. S., & Tsai, M. C. (2021). Effects of design thinking on artificial intelligence learning and creativity. *Educational Studies*, 1–18.

Chen, X., Zou, D., Xie, H., Cheng, G., & Liu, C. (2022). Two Decades of Artificial Intelligence in Education. *Educational Technology & Society, 25*(1), 28–47.

Chiang, A. (2007). Motivate AI class with interactive computer games. In *2007 first IEEE international workshop on digital game and intelligent toy enhanced learning* (DIGITEL'07) (pp. 109–113). IEEE.

Chiu, T. K., & Chai, C. S. (2020). Sustainable curriculum planning for artificial intelligence education: A self-determination theory perspective. *Sustainability, 12*(14), 5568.

Chiu, T. K., Meng, H., Chai, C. S., King, I., Wong, S., & Yam, Y. (2021). Creation and evaluation of a pretertiary artificial intelligence (AI) curriculum. *IEEE Transactions on Education, 65*(1), 30–39.

Cicirello, V. A. (2008). An interdisciplinary course on artificial intelligence designed for a liberal arts curriculum. *Journal of Computing Sciences in Colleges, 23*(3), 120–127.

Coelho, H. & Cotta, J. C. (2012). *Prolog by example: How to learn, teach and use it*. Springer Science & Business Media.
Denenberg, S. A. (1985). A service project for an introductory artificial intelligence course: Implementing SOLO in LOGO. *ACM SIGCSE Bulletin, 17*(4), 8–20.
DeNero, J., & Klein, D. (2010). Teaching introductory artificial intelligence with Pac-man. In First AAAI Symposium on Educational Advances in Artificial Intelligence.
DigComp. (2022). *DigComp 2.2: The Digital Competence Framework for Citizens - With new examples of knowledge, skills and attitudes*. Retrieved from https://publications.jrc.ec.europa.eu/repository/handle/JRC128415
Dodds, Z. (2008). AI assignments in a CS1 course: Reflections and evaluation. *Journal of Computing Sciences in Colleges, 23*(6), 262–271.
Druga, S., Vu, S. T., Likhith, E. & Qiu, T. (2019). Inclusive AI literacy for kids around the world. In *Proceedings of FabLearn 2019* (pp. 104–111).
Estevez, J., Garate, G., & Graña, M. (2019). Gentle introduction to artificial intelligence for high-school students using Scratch. *IEEE Access, 7*, 179027–179036.
Fernandes, M. A. (2016). Problem-based learning applied to the artificial intelligence course. *Computer Applications in Engineering Education, 24*(3), 388–399.
Fjelland, R. (2020). Why general artificial intelligence will not be realized. *Humanities and Social Sciences Communications, 7*(1), 1–9.
Floridi, L., Cowls, J., Beltrametti, M., Chatila, R., Chazerand, P., Dignum, V., …, & Schafer, B. (2018). AI4People—An ethical framework for a good AI society: Opportunities, risks, principles, and recommendations. *Minds and Machines, 28*(4), 689–707.
Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education, 27*(7), 855–879.
French, R. M. (2000). The Turing test: The first 50 years. *Trends in Cognitive Sciences, 4*(3), 115–122.
García, R. M. C., Román, J. V., & Pardo, A. (2006). Peer review to improve artificial intelligence teaching. In Proceedings. Frontiers in Education. 36th Annual Conference (pp. 3–8). IEEE.
Glaser, B. G. (1965). The constant comparative method of qualitative analysis. *Social Problems 12,* (4), 436–445.
Goel, A. K., & Joyner, D. A. (2017). Using AI to teach AI: Lessons from an online AI class. *AI Magazine, 38*(2), 48–59.
Greenwald, E., Leitner, M., & Wang, N. (2021). Learning artificial intelligence: insights into how youth encounter and build understanding of AI concepts. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 35, No. 17, pp. 15526–15533).
Hadim, H. A. & Esche, S. K. (2002). Enhancing the engineering curriculum through project-based learning. In *32nd annual frontiers in education* (Vol. 2, pp. F3F-F3F). IEEE.
Hammond, J., & Gibbons, P. (2005). What is scaffolding? *Teachers' Voices, 8*, 8–16.
Hartness, K. (2004). Robocode: Using games to teach artificial intelligence. *Journal of Computing Sciences in Colleges, 19*(4), 287–291.
Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of educational research, 77*(1), 81–112.
Henry, J., Hernalesteen, A., & Collard, A. S. (2021). Teaching artificial intelligence to K-12 through a role-playing game questioning the intelligence concept. *KI-Künstliche Intelligenz, 35*(2), 171–179.
Hew, K. F., & Cheung, W. S. (2014). Students' and instructors' use of massive open online courses (MOOCs): Motivations and challenges. *Educational Research Review, 12*, 45–58.
Hill, J. M., & Alford, K. L. (2004). A distributed task environment for teaching artificial intelligence with agents. *ACM SIGCSE Bulletin, 36*(1), 224–228.
Hind, M., Wei, D., Campbell, M., Codella, N. C. F., Dhurandhar, A., Mojsilović, A., Ramamurthy, K. N. & Varshney, K. R. (2019). TED: Teaching AI to explain its decisions. In *Proceedings of the 2019 AAAI/ACM conference on AI, ethics, and society*, pp. 123–129.
Huang, X. (2021). Aims for cultivating students' key competencies based on artificial intelligence education in China. *Education and Information Technologies, 26*(5), 5127–5147.
Imberman, S. P. (2005). Three fun assignments for an artificial intelligence class. *Journal of Computing Sciences in Colleges, 21*(2), 113–118.
Imberman, S. P. (2004). An intelligent agent approach for teaching neural networks using LEGO® handy board robots. *Journal on Educational Resources in Computing* (JERIC), *4*(3), 4-es.

Impagliazzo, J. (2020). Why Teach History of Computing?. *Encyclopedia of Education and Information Technologies*, 1786–1791.

International Society for Technology in Education (ISTE). (2022). *Hands-on AI projects for the classroom.* Retrieved from https://cdn.iste.org/www-root/Libraries/Documents%20%26%20Files/Artificial%20Intelligence/AIGDK5_1120.pdf

Jang, Y., Choi, S., & Kim, H. (2022). Development and validation of an instrument to measure undergraduate students' attitudes toward the ethics of artificial intelligence (AT-EAI) and analysis of its difference by gender and experience of AI education. *Education and Information Technologies*, 1–33.

Jobin, A., Ienca, M., & Vayena, E. (2019). The global landscape of AI ethics guidelines. *Nature Machine Intelligence, 1*(9), 389–399.

Kandlhofer, M., Steinbauer, G., Laßnig, J. P., Baumann, W., Plomer, S., Ballagi, A., & Alfoldi, I. (2019). Enabling the creation of intelligent things: Bringing artificial intelligence and robotics to schools. In *2019 IEEE Frontiers in Education Conference (FIE)* (pp. 1–5). IEEE.

Kapp, K. M. (2012). *The gamification of learning and instruction: Game-based methods and strategies for training and education.* John Wiley & Sons.

Kim, S., Jang, Y., Kim, W., Choi, S., Jung, H., Kim, S., & Kim, H. (2021). Why and what to teach: AI curriculum for elementary school. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 35, No. 17, pp. 15569–15576).

Klassner, F. (2002). A case study of LEGO MindStorms'™ suitability for artificial intelligence and robotics courses at the college level. In *Proceedings of the 33rd SIGCSE technical symposium on computer science education* (pp. 8–12).

Kong, S. C., Cheung, W. M. Y., & Zhang, G. (2021). Evaluation of an artificial intelligence literacy course for university students with diverse study backgrounds. *Computers and Education: Artificial Intelligence, 2*, 100026.

Kozak, M. M. (2006). Teaching artificial intelligence using Web-based applications. *Journal of Computing Sciences in Colleges, 22*(1), 46–53.

Krajcik, J. S. & Blumenfeld, P. C. (2006). Project-based learning. In *The Cambridge handbook of the learning sciences* (pp. 317–334). Cambridge University Press.

Kumar, A., Kumar, D., & Russell, I. (2006). Non-traditional projects in the undergraduate AI course. *ACM SIGCSE Bulletin, 38*(1), 479–480.

Kumar, A. N. (2001). Using robots in an undergraduate artificial intelligence course: An experience report. In *31st annual frontiers in education conference. Impact on engineering and science education. Conference proceedings* (Cat. No. 01CH37193) (Vol. 2, pp. T4D-10). IEEE.

Laal, M., & Ghodsi, S. M. (2012). Benefits of collaborative learning. *Procedia-Social and Behavioral Sciences, 31*, 486–490.

Laupichler, M. C., Aster, A., Schirch, J., & Raupach, T. (2022). Artificial intelligence literacy in higher and adult education: A scoping literature review. *Computers and Education: Artificial Intelligence*, 100101.

League, C. (2008). Something for everyone: AI lab assignments that span learning styles and aptitudes. *Journal of Computing Sciences in Colleges, 23*(5), 142–149.

Lee, I., Ali, S., Zhang, H., DiPaola, D. & Breazeal, C. (2021). Developing middle school students' AI literacy. In *Proceedings of the 52nd ACM technical symposium on computer science education* (pp. 191–197).

Leonard, J., Buss, A., Gamboa, R., Mitchell, M., Fashola, O. S., Hubert, T., & Almughyirah, S. (2016). Using robotics and game design to enhance children's self-efficacy, STEM attitudes, and computational thinking skills. *Journal of Science Education and Technology, 25*(6), 860–876.

Lester, S. & Russell, W. (2008). *Play for a change: Play, policy and practice. A review of contemporary perspectives.* National Children's Bureau Enterprises Ltd.

Li, Z., O'Brien, L., Flint, S., & Sankaranarayana, R. (2014). Object-oriented Sokoban solver: A serious game project for OOAD and AI education. In *2014 IEEE Frontiers in Education Conference (FIE) Proceedings* (pp. 1–4). IEEE.

Lichtenthaler, U. (2018). Substitute or synthesis: The interplay between human and artificial intelligence. *Research-Technology Management, 61*(5), 12–14.

Lin, P. Y., Chai, C. S., Jong, M. S. Y., Dai, Y., Guo, Y., & Qin, J. (2021). Modeling the structural relationship among primary students' motivation to learn artificial intelligence. *Computers and Education: Artificial Intelligence, 2*, 100006.

Linden, J., Erkens, G., Schmidt, H. & Renshaw, P. (2000). Collaborative learning. In *New learning* (pp. 37–54). Springer.
Long, D., & Magerko, B. (2020). What is AI literacy? Competencies and design considerations. In *Proceedings of the 2020 CHI conference on human factors in computing systems* (pp. 1–16).
Long, D., Jacob, M., & Magerko, B. (2019). Designing co-creative AI for public spaces. In *Proceedings of the 2019 on Creativity and Cognition* (pp. 271–284).
Long, D., Blunt, T., & Magerko, B. (2021a). Co-designing AI literacy exhibits for informal learning spaces. *Proceedings of the ACM on Human-Computer Interaction*, *5*(CSCW2), 1–35.
Long, D., Padiyath, A., Teachey, A., & Magerko, B. (2021b). The role of collaboration, creativity, and embodiment in AI learning experiences. In *Creativity and cognition* (pp. 1–10).
Ma, W., Adesope, O. O., Nesbit, J. C., & Liu, Q. (2014). Intelligent tutoring systems and learning outcomes: A meta-analysis. *Journal of Educational Psychology, 106*(4), 901.
Maheshwari, A., Bhansali, A., Rajamani, S., Srinivasan, S., Srivathsa, R., Gupta, A., Shetty, J., Dhakad, K., Chadha, A., Kambhampati, R. S., Thirumalai-Anandanpillai, T. & Gupta, P. (2019). *Microsoft AI whitepaper age of intelligence.* Retrieved from https://news.microsoft.com/wp-content/uploads/prod/sites/45/2019/02/Microsoft-AI-Whitepaper-Age-of-Intelligence.pdf
Mauch, E. (2001). Using technological innovation to improve the problem-solving skills of middle school students. *The Clearing House, 75*(4), 211–213.
McCarthy, J. (2007). From here to human-level AI. *Artificial Intelligence, 171*(18), 1174–1182.
McGovern, A. & Fager, J. (2007, March). Creating significant learning experiences in introductory artificial intelligence. In *Proceedings of the 38th SIGCSE technical symposium on computer science education* (pp. 39–43).
McGovern, A., Tidwell, Z. & Rushing, D. (2011, August). Teaching introductory artificial intelligence through Java-based games. In *AAAI symposium on educational advances in artificial intelligence, North America*.
McKee, G. T. (2002, May). The development of Internet-based laboratory environments for teaching robotics and artificial intelligence. In *Proceedings* 2002 *IEEE international conference on robotics and automation* (Cat. No. 02CH37292) (Vol. 3, pp. 2695–2700). IEEE.
Menzies, T. (2003). 21st-century AI: Proud, not smug. *IEEE Intelligent Systems, 18*(3), 18–24.
Merzbacher, M. (2001, February). Open artificial intelligence-one course for all. In *Proceedings of the thirty-second SIGCSE technical symposium on computer science education* (pp. 110–113).
Michaud, L. N. (2014). Evil robots and helpful droids: A seminar for a junior/senior artificial intelligence course. *Journal of Computing Sciences in Colleges, 29*(6), 123–129.
Microsoft. (2021). *FATE: Fairness, accountability, transparency, and ethics in AI.* Retrieved from https://www.microsoft.com/en-us/research/theme/fate
Miles, M. B. & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Sage.
Minsky, M. (2019). *Inventive minds: Marvin Minsky on education.* Edited by Solomon, C. and Xiao, X., MIT Press.
Mota-Valtierra, G., Rodríguez-Reséndiz, J., & Herrera-Ruiz, G. (2019). Constructivism-based methodology for teaching artificial intelligence topics focused on sustainable development. *Sustainability, 11*(17), 4642.
Munna, A. S., & Kalam, M. A. (2021). Teaching and Learning Process to Enhance Teaching Effectiveness: A Literature Review. *Online Submission, 4*(1), 1–4.
Narahara, T. & Kobayashi, Y. (2018). Personalizing homemade bots with plug & play AI for STEAM education. In *SIGGRAPH Asia 2018 Technical Briefs* (pp. 1–4).
National Research Council (NRC). (2001). *Classroom assessment and the national science education standards*. National Academies Press.
Ng, D. T. K., & Chu, S. K. W. (2021). Motivating students to learn AI through social networking sites: A case study in Hong Kong. *Online Learning, 25*(1), 195–208.
Ng, D. T. K., Leung, J. K. L., Chu, K. W. S., & Qiao, M. S. (2021a). AI literacy: Definition, teaching, evaluation and ethical issues. *Proceedings of the Association for Information Science and Technology, 58*(1), 504–509.
Ng, D. T. K., Leung, J. K. L., Chu, S. K. W., & Qiao, M. S. (2021b). Conceptualizing AI literacy: An exploratory review. *Computers and Education: Artificial Intelligence, 2*, 100041.
Ng, D. T. K., Leung, J. K. L, Su, J., Yim, H. Y., Shen, Q., & Chu, S. K. W. (2022a). *AI literacy in K-16 Classroom*. Springer Nature.

Ng, D. T. K., Luo, W., Chan, H. M. Y., & Chu, S. K. W. (2022b). Using digital story writing as a pedagogy to develop AI literacy among primary students. *Computers and Education: Artificial Intelligence, 3*, 100054.
Nicol, D. J., & Macfarlane-Dick, D. (2006). Formative assessment and self-regulated learning: A model and seven principles of good feedback practice. *Studies in Higher Education, 31*(2), 199–218.
Noriega Campero, A. (2019). *Human and artificial intelligence in decision systems for social development* (Doctoral dissertation, Massachusetts Institute of Technology).
Normadhi, N. B. A., Shuib, L., Nasir, H. N. M., Bimba, A., Idris, N., & Balakrishnan, V. (2019). Identification of personal traits in an adaptive learning environment: Systematic literature review. *Computers & Education, 130*, 168–190.
Norvig, P. (1992). *Paradigms of artificial intelligence programming: Case studies in common LISP*. Morgan Kaufmann.
Nye, B. D. (2015). Intelligent tutoring systems by and for the developing world: A review of trends and approaches for educational technology in a global context. *International Journal Artificial Intelligence Education, 25*, 177–203. https://doi.org/10.1007/s40593-014-0028-6
OECD. (2013). Student assessment: Putting the learner at the centre. In *Synergies for better learning: An international perspective on evaluation and assessment*. OECD Publishing.
Office of Science and Technology Policy (OSTP). (2019). *2016–2019 progress report: Advanced artificial intelligence research and development.* Retrieved from https://www.whitehouse.gov/wp-content/uploads/2019/11/AI-Research-and-Development-Progress-Report-2016-2019.pdf
Özdemir, V. & Hekim, N. (2018). Birth of industry 5.0: Making sense of big data with artificial intelligence, the internet of things and next-generation technology policy. *Omics: A Journal of Integrative Biology*, *22*(1), 65–76.
Pantic, M., Zwitserloot, R., & Grootjans, R. J. (2005). Teaching introductory artificial intelligence using a simple agent framework. *IEEE Transactions on Education, 48*(3), 382–390.
Papert, S., Solomon, C., Soloway, E. & Spohrer, J. C. (1971). Twenty things to do with a computer. In *Studying the novice programmer* (pp. 3–28). Lawrence Erlbaum Associates, Inc.
Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism, 36*(2), 1–11.
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* Basic Books, Inc.
Paxton, J. T. (1995). A novel approach to teaching artificial intelligence. *ACM SIGCSE Bulletin, 27*(1), 283–286.
Pedro, F., Subosa, M., Rivas, A. & Valverde, P. (2019). Artificial intelligence in education: Challenges and opportunities for sustainable development. United Nations Educational, Scientific and Cultural Organization.
Peña, C. I., Marzo, J. L. & De la Rosa, J. L. (2005). Intelligent agents to improve adaptivity in a Web-based learning environment. In *Knowledge-based virtual education* (pp. 141–170). Springer.
Polpanumas, C., Limkonchotiwat, P., Matupumanon, B., Chaksangchaichot, C., Chumlek, N., Phaphoom, N., & Achakulvisut, T. (2021). AI builders: Teaching Thai students to build end-to-end machine learning projects online. In *2021 IEEE International Conference on Engineering, Technology & Education (TALE)* (pp. 565–572). IEEE.
Popescu, E., & Badica, C. (2011). Creating a personalized artificial intelligence course: WELSA case study. *International Journal of Information Systems and Social Change (IJISSC), 2*(1), 31–47.
Ribeiro, P. M. P., Simões, H., & Ferreira, M. (2009). Teaching artificial intelligence and logic programming in a competitive environment. *Informatics in Education, 8*(1), 85–100.
Rina, R., Kluzer, S., & Punie, Y. (2022). *DigComp 2.2: The Digital Competence Framework for Citizens-With new examples of knowledge, skills and attitudes* (No. JRC128415). Joint Research Centre (Seville site).
Roll, I., & Wylie, R. (2016). Evolution and revolution in artificial intelligence in education. *International Journal of Artificial Intelligence in Education, 26*(2), 582–599.
Romero, C., & Ventura, S. (2020). Educational data mining and learning analytics: An updated survey. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 10*(3), e1355.
Rowe, N. C. (1988). *Artificial intelligence through Prolog.* Faculty and Researcher Publications, Dudley Knox Library. Retrieved from https://core.ac.uk/download/pdf/36729469.pdf.
Russell, S., & Norvig, P. (1995). A modern, agent-oriented approach to introductory artificial intelligence. *ACM Sigart Bulletin, 6*(2), 24–26.
Russell, S. & Norvig, P. (2002). *Artificial intelligence: A modern approach.* Pearson Education.

Sabuncuoglu, A. (202). Designing one year curriculum to teach artificial intelligence for middle school. In *Proceedings of the 2020 ACM conference on innovation and technology in computer science education* (pp. 96–102).

Sailer, M., Hense, J. U., Mayr, S. K., & Mandl, H. (2017). How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction. *Computers in Human Behavior, 69*, 371–380.

Saiyeda, A., & Mir, M. A. (2017). Cloud computing for deep learning analytics: A survey of current trends and challenges. *International Journal of Advanced Research in Computer Science, 8*(2), 68–72.

Sakulkueakulsuk, B., Witoon, S., Ngarmkajornwiwat, P., Pataranutaporn, P., Surareungchai, W., Pataranutaporn, P. & Subsoontorn, P. (2018, December). Kids making AI: Integrating machine learning, gamification, and social context in STEM education. In *2018 IEEE international conference on teaching, assessment, and learning for engineering* (pp. 1005–1010). IEEE.

Salkind, N. J. (Ed.). (2010). *Encyclopedia of research design* (Vol. 1). Sage. https://doi.org/10.4135/9781412961288.n60

Sánchez-Nielsen, E. & Klink, S. (2011). Integrating Google technology in artificial intelligence. In *Proceedings of the 16th annual joint conference on innovation and technology in computer science education* (pp. 108–112).

Sanusi, I. T., Olaleye, S. A., Agbo, F. J., & Chiu, T. K. (2022). The role of learners' competencies in artificial intelligence education. *Computers and Education: Artificial Intelligence, 3*, 100098.

Scheessele, M. R. & Schriefer, T. (2006). Poker as a group project for artificial intelligence. In *Proceedings of the 37th SIGCSE technical symposium on computer science education* (pp. 548–552).

Sharma, S. (2021). 2021 was a breakthrough year for AI. Retrieved from https://venturebeat.com/ai/2021-was-a-breakthrough-year-for-ai/

Shaw, M. (2000). Software engineering education: A roadmap. In *Proceedings of the conference on the future of software engineering* (pp. 371–380).

Siau, K., & Wang, W. (2020). Artificial intelligence (AI) ethics: Ethics of AI and ethical AI. *Journal of Database Management (JDM), 31*(2), 74–87.

Silapachote, P. & Srisuphab, A. (2014, April). Gaining and maintaining student attention through competitive activities in cooperative learning: A well-received experience in an undergraduate introductory artificial intelligence course. In *2014 IEEE global engineering education conference* (EDUCON) (pp. 295–298). IEEE.

Sintov, N. D., Kar, D., Nguyen, T. H., Fang, F., Hoffman, K., Lyet, A. & Tambe, M. (2016, February). From the lab to the classroom and beyond: Extending a game-based research platform for teaching AI to diverse audiences. In *Association for the advancement of artificial intelligence*, *2016* (pp. 4107–4112).

Stahl, B. C., & Wright, D. (2018). Ethics and privacy in AI and big data: Implementing responsible research and innovation. *IEEE Security & Privacy, 16*(3), 26–33.

Stebbins, R. A. (2001). *Exploratory research in the social sciences* (Vol. 48). Sage.

Steenbergen-Hu, S., & Cooper, H. (2014). A meta-analysis of the effectiveness of intelligent tutoring systems on college students' academic learning. *Journal of Educational Psychology, 106*(2), 331.

Straub, J., Kerlin, S. & Kim, E. (2017, May). Analysis of student characteristics and feeling of efficacy in a first undergraduate artificial intelligence course. In *2017 IEEE international conference on electro information technology* (pp. 010–015). IEEE.

Su, J., & Yang, W. (2022). Artificial intelligence in early childhood education: A scoping review. *Computers and Education: Artificial Intelligence*, 100049.

Su, J., Zhong, Y., & Ng, D. T. K. (2022). A meta-review of literature on educational approaches for teaching AI at the K-12 levels in the Asia-Pacific region. *Computers and Education: Artificial Intelligence*, 100065.

Swoboda, N., Bekios-Calfa, J., Baumela, L. & de Lope, J. (2011, March). An introduction to AI course with guide robot programming assignments. In *Proceedings of the 42nd ACM technical symposium on computer science education* (pp. 231–236).

Tan, S. C., Lee, A. V. Y., & Lee, M. (2022). A systematic review of artificial intelligence techniques for collaborative learning over the past two decades. *Computers and Education: Artificial Intelligence*, 100097.

Toh, L. P. E., Causo, A., Tzuo, P. W., Chen, I. M., & Yeo, S. H. (2016). A review on the use of robots in education and young children. *Journal Education Technology Society, 19*, 148–163.

Toivonen, T., Jormanainen, I., Kahila, J., Tedre, M., Valtonen, T. & Vartiainen, H. (2020). Co-designing machine learning apps in K-12 with primary school children. In *2020 IEEE: 20th international conference on advanced learning technologies* (pp. 308–310). IEEE.

Touretzky, D., Gardner-McCune, C., Martin, F. & Seehorn, D. (2019). Envisioning AI for K-12: What should every child know about AI? In *Proceedings of the AAAI conference on artificial intelligence* (Vol. 33, pp. 9795–9799).

Trilling, B. & Fadel, C. (2009). *21st century skills: Learning for life in our times.* John Wiley & Sons.

Turing, A. M. (1950). Computing machinery and intelligence. *Mind: A Quarterly Review of Psychology and Philosophy*, 59, 433–460.

UNESCO (2019). Artificial intelligence for sustainable development programme. Retrieved from https://en.unesco.org/sites/default/files/mlw2019-programme.pdf.

UNESCO (2021). K-12 AI curricula: a mapping of government-endorsed AI curricula. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000380602

Van Brummelen, J., Heng, T., & Tabunshchyk, V. (2021). Teaching tech to talk: K-12 conversational artificial intelligence literacy curriculum and development tools. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 35, No. 17, pp. 15655–15663).

Vaughan, J. W. & Wallach, H. (2020). A human-centered agenda for intelligible machine learning. In *Machines we trust: Getting along with artificial intelligence*. Retrieved from https://www.microsoft.com/en-us/research/publication/a-human-centered-agenda-for-intelligible-machine-learning/

Voulgari, I., Zammit, M., Stouraitis, E., Liapis, A., & Yannakakis, G. (2021). Learn to machine learn: designing a game based approach for teaching machine learning to primary and secondary education students. In *Interaction design and children* (pp. 593–598).

Wallace, S. A., McCartney, R., & Russell, I. (2010). Games and machine learning: A powerful combination in an artificial intelligence course. *Computer Science Education, 20*(1), 17–36.

Walsh K. (2019). *Rethinking Weak Vs. Strong AI.* In *Forbes.* Retrieved from https://www.forbes.com/sites/cognitiveworld/2019/10/04/rethinking-weak-vs-strong-ai/?sh=52b5fbb46da3

Wang, P. (2019). On defining artificial intelligence. *Journal of Artificial General Intelligence, 10*(2), 1–37.

Wang, Y. (2021). When artificial intelligence meets educational leaders' data-informed decision-making: A cautionary tale. *Studies in Educational Evaluation, 69*, 100872.

Wangenheim, C., Hauck, J. C., Pacheco, F. S., & Bertonceli Bueno, M. F. (2021). Visual tools for teaching machine learning in K-12: A ten-year systematic mapping. *Education and Information Technologies, 26*(5), 5733–5778.

Watkins, T. (2020). Cosmology of artificial intelligence project: Libraries, makerspaces, community and AI literacy. *AI Matters, 5*(4), 14–17.

Weidong, Z., Haifeng, W. & Anhua, W. (2009). Research-based teaching in an artificial intelligence course. In *2009 4th international conference on computer science & education* (pp. 1756–1759). IEEE.

Weintrop, D. & Wilensky, U. (2015). To block or not to block, that is the question: Students' perceptions of blocks-based programming. In *Proceedings of the 14th international conference on interaction design and children* (pp. 199–208).

Williams, S., Terras, M., & Warwick, C. (2013). What people study when they study Twitter: Classifying Twitter-related academic papers. *Journal of Documentation, 69*(3), 384–410.

Williams, R., Park, H. W., Oh, L. & Breazeal, C. (2019). Popbots: Designing an artificial intelligence curriculum for early childhood education. In *Proceedings of the AAAI conference on artificial intelligenc*e (Vol. 33, pp. 9729–9736).

Winston, P. H. & Horn, B. K. (1986). *LISP.* Second edition. United States. Retrieved from https://www.osti.gov/biblio/7203980

Wolfer, J. (2019). A biomedical motif for teaching applied deep learning. In the *2019, 5th experiment international conference* (pp. 332–336). IEEE.

Wong, D., Zink, R. & Koenig, S. (2010). Teaching artificial intelligence and robotics via games. In *Proceeding of the engineering applications of artificial intelligence symposium.*

Wood, E. A., Ange, B. L., & Miller, D. D. (2021). Are we ready to integrate artificial intelligence literacy into medical school curriculum: Students and faculty survey. *Rove Artificial Intelligence*.

Xia, Q., Chiu, T. K., Lee, M., Sanusi, I. T., Dai, Y., & Chai, C. S. (2022). A self-determination theory (SDT) design approach for inclusive and diverse artificial intelligence (AI) education. *Computers & Education, 189*, 104582.

Xie, H., Chu, H. C., Hwang, G. J., & Wang, C. C. (2019). Trends and development in technology-enhanced adaptive/personalized learning: A systematic review of journal publications from 2007 to 2017. *Computers & Education, 140*, 103599.
Xu, J. J., & Babaian, T. (2021). Artificial intelligence in business curriculum: The pedagogy and learning outcomes. *The International Journal of Management Education, 19*(3), 100550.
Yang, W. (2022). Artificial intelligence education for young children: Why, what, and how in curriculum design and implementation. *Computers and Education: Artificial Intelligence, 3*, 100061.
Yazdani, M., editor, (1984). *New horizons in educational computing*. Halsted Press.
Yue, K. B. (1989). Using the game Cube-4 as an example in an introductory artificial intelligence course. *ACM SIGCSE Bulletin, 21*(3), 8–10.
Zainuddin, Z., Chu, S. K. W., Shujahat, M., & Perera, C. J. (2020). The impact of gamification on learning and instruction: A systematic review of empirical evidence. *Educational Research Review, 30*, 100326.
Zammit, M., Voulgari, I., Liapis, A., & Yannakakis, G. N. (2021). The road to AI literacy education: from pedagogical needs to tangible game design. In *Academic Conferences International*. Retrieved from https://www.um.edu.mt/library/oar/handle/123456789/80765
Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education – Where are the educators? *International Journal of Educational Technology in Higher Education, 16*(1), 39.
Zeng, J., & Xie, P. (2021). Contrastive self-supervised learning for graph classification. In Proceedings of the AAAI Conference on Artificial Intelligence (Vol. 35, No. 12, pp. 10824-10832).

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