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The key artificial intelligence technologies in early childhood education: a review

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Abstract
Artificial Intelligence (AI) technologies have been applied in various domains, including early childhood education (ECE). Integration of AI educational technology is a recent significant trend in ECE. Currently, there are more and more studies of AI in ECE. To date, there is a lack of survey articles that discuss the studies of AI in ECE. In this paper, we provide an up-to-date and in-depth overview of the key AI technologies in ECE that provides a historical perspective, summarizes the representative works, outlines open questions, discuss the trends and challenges through a detailed bibliometric analysis, and provides insightful recommendations for future research. We mainly discuss the studies that apply AI-based robots and AI technologies to ECE, including improving the social interaction of children with an autism spectrum disorder. This paper significantly contributes to provide an up-to-date and in-depth survey that is suitable as introductory material for beginners to AI in ECE, as well as supplementary material for advanced users.

Keywords Artificial Intelligence · Early childhood education · Educational technology · Improving classroom teaching · Teaching/learning strategies

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1 Introduction

In recent years, Artificial Intelligence (AI) is revolutionizing the way of human life (Williams et al. 2018), in particular the education domain. In the AI era, using AI technology in education is a significant trend. AI educational technologies play an important role in modern education by providing unique learning experiences to students and improving their learning (Prentzas 2013). AI approaches have been incorporated into educational technologies for improving interaction with students and employed in an educational context to satisfy various educational needs (Roblyer and Doering 2007). AI educational technologies provide students and teachers benefits compared to traditional education, including inspiring students' motives for creative activities (Prentzas 2013), avoiding shame and embarrassment in front of their peers, assisting teachers to provide students with personalized self-adaptive learning (Xu 2020) and remove repetitive tasks and value-add to meaningful teaching tasks.

Early childhood is a wonderful time to spark children's interest in AI (Su and Yang 2022). Among all stages of education, early childhood education (ECE) is particularly important because they first learn how to interact with others including peers and teachers, and begin to develop interests that will inspire them throughout their lives. ECE generally set the stage for future educational success in secondary education and higher education (Gammage 2006). For the formative years of ECE, creating a modern environment where children learn fundamental skills is crucial for their future success. Integration of AI concepts in ECE is significantly crucial to how children realize AI in future (Su and Yang 2022). Although there are a few existing survey articles that reviewed the studies of AI in related education (e.g., music education, medical education), there is a lack of survey articles that discuss the studies of AI in ECE. In this paper, we summarize the representative studies of popular intelligent robots, and main AI technologies in ECE, analyses challenges and trends by bibliometric, and provides insightful recommendations for future research. This paper significantly contributes to provide an up-to-date and in-depth survey that is suitable as introductory material for beginners to AI in ECE, as well as supplementary material for advanced users.

1.1 Related review

In the early literature, Holland (2000) reviews the principal approaches of AI in music education. Chassignol et al. (2012) and Drigas and Ioannidou (2011) discuss the studies of AI in special education over the last decade (2001–2010). In 2013, a survey article (Prentzas 2013) claims to review the studies of AI methods in early childhood educational technology, which mainly concerns computer-based learning systems rather than focusing on AI in ECE.

Recently, Huijnen et al. (2017a) review the studies about AI-based robots that are used in therapy and education for children with Autism Spectrum Disorder (ASD). Chassignol et al. (2018) identify the prospective impact of AI technologies on the studying process and predict the trends in education. Chan and Zary (2019) review the current AI applications and the challenges of implementing AI in medical education. Zawacki-Richter et al. (2019) review the studies of AI applications in higher education. Zaidi et al. (2019) provides an overview of the effectiveness of online learning and AI in education. Chen et al. (2020a) provide an overview to assess the impact of AI in education. In Sapci and Sapci (2020), the authors present a review to evaluate the current state of AI training and the use of AI tools to enhance the learning experience for medical and health informatics students. Chen et al. (2020b) review the studies of AI in education in terms of applications and theory gaps. In Buchanan et al. (2021), the authors summarize the current studies and predict the influences of AI health technologies on nursing education over the next 10 years and beyond. Maghsudi et al. (2021) provide a brief review of the state-of-the-art studies to observe the challenges of AI/ML-based personalized education and discuss potential solutions.

Especially, Ahmad et al. (2020) review the studies of AI in secondary education and higher education by highlighting the future scope and market opportunities for AI in education, the existing tools, research trends, current limitations, and pitfalls of AI in education. Although these existing survey articles review the studies of AI in education including the domains of special education, music education, medical education, and nursing education, there is a lack of survey articles that review the studies of AI in early childhood education. The comparison of the previous surveys of AI in education and the position of our work is shown in Table 1 which presents the covered topics, whether the research trends and challenges and bibliometrics are included. In particular, only two articles (Chen et al. 2020b; Ahmad et al. 2020) of them provide detailed bibliometrics analysis and many existing review articles (Holland 2000; Chassignol et al. 2012; Drigas and Ioannidou 2011; Prentzas 2013; Huijnen et al. 2017a; Chen et al. 2020a; Sapci and Sapci 2020; Buchanan et al. 2021) of them do not even discuss trends and challenges. Although the article (Ahmad et al. 2020) discusses trends and challenges with bibliometrics, it focuses on the future scope and market opportunities of AI in secondary education and higher education. This survey fills a gap in the existing review articles of AI in education.

1.2 Contributions

We emphasize that a comprehensive and solid overview of AI in early childhood education topics should review the representative articles, discuss challenges, provide detailed bibliometrics analysis, and observe trends for further research. As shown in Table 1, although trends and challenges are crucial in an overview, a few current articles analyse both trends and challenges. In particular, bibliometrics is rarely applied to analyse the existing studies of AI in ECE. The main contributions of the work are summarized as follows:

1. Delineate the picture of AI in ECE.
2. Provide a complete/detailed overview of the existing literature on AI in ECE.
3. Identify the challenges and analyze the research trends for future developments by bibliometrics.

This paper provides an up-to-date and in-depth overview that is suitable as introductory material for beginners to AI in ECE, as well as supplementary material for advanced users. Figure 1 shows the taxonomy of this survey, where the picture of AI in ECE is clearly presented for readers to quickly figure out the structure of this survey. Specifically, the rest of this paper is organized as follows. In Sect. 3, we present the popular intelligent robots that are used for ECE. The main AI technologies such as data mining, machine learning, and deep learning for AI in ECE are summarized in Sect. 4. We address the bibliometric analysis in Sect. 2. Challenges and trends are discussed in Sect. 5. Finally, we conclude this paper in Sect. 6.

Table 1 Overview of previous review articles of AI in education (AIEd) and the position of ours (this review)

Article	Methods	Topics	Trends	Challenges	Bibliometrics
Prentzas (2013)	Computer-based	Early childhood education	–	–	–
Holland (2000)	AI	Music education	–	–	–
Chassignol et al. (2012) and Drigas and Ioannidou (2011)	AI	Special education	–	–	–
Huijnen et al. (2017a)	Robots	ASD	–	–	–
Chassignol et al. (2018)	AI	AIEd trends	✓	–	–
Zawacki-Richter et al. (2019)	AI Applications	Higher education	–	✓	–
Zaidi et al. (2019)	AI & Online learning	AIEd market	✓	✓	–
Chan and Zary (2019)	AI	Medical education	–	✓	–
Chen et al. (2020a)	AI	AIEd	–	–	–
Sapci and Sapci (2020)	AI training & tools	Medical education	–	–	–
Chen et al. (2020b)	AI	AIEd	✓	–	✓
Ahmad et al. (2020)	AI	Market & outlook	✓	✓	✓
Buchanan et al. (2021)	AI health technologies	Nursing education	–	–	–
Maghsudi et al. (2021)	AI/ML	Personalized education	–	✓	–
Ours	AI-based	**Early childhood education**	✓	✓	✓

✓ (–) represents that the review paper has (not) discussed the content

The bold text highlights the position of ours

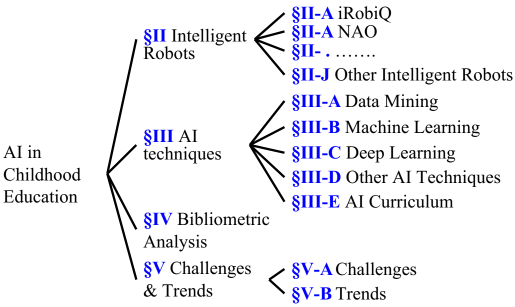

Fig. 1 Taxonomy of this survey on AI for early childhood education

2 Bibliometric analysis

Bibliometrics is the use of statistical methods to analyse books, articles and other publications. It is an effective way to measure the information of publication in the scientific community (Iftikhar et al. 2019). However, current survey papers rarely use bibliometrics to analyse the studies, particularly AI in ECE. In general, bibliometric data can be obtained from various databases such as PubMed, Web of Science, and Google Scholar. In this paper, we choose the Scopus database for literature retrieval. Scopus is the largest abstract/citation database with peer-reviewed literature and covers a wider journal range, of help both in keyword searching and citation analysis (Falagas et al. 2008), which is released by Elsevier. Importantly, Elsevier provides a Python library[1] to retrieve the data for the expected topics from the Scopus database (Rose and Kitchin 2019). In this work, we review the articles about AI in ECE by retrieving the format of "title, abstract, and keywords" in the Scopus database.

We retrieve the literature on this topic by combining keywords by the search code of title-abs-key(("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "data mining" OR "virtual reality" OR "natural language processing" OR "robot" OR "robots") AND ("early childhood education" OR "autism" OR "autism spectrum disorder" OR "ASD" OR "preschool" OR "kindergarten")). To observe the trends clearly, we retrieve the data for each year over 10 years from 2010 to date. The number of publications over the years (from 2010 to 2022) is shown in Fig. 2. The dashed red lines are the cubic polynomial fit of the number of publications. The number of publications shows a clear growth trend from 2010 to 2021, while an insignificant drop in 2012 and 2016. In particular, it shows a significant increase in recent years from 2017 to 2021 which is the outbreak period of AI. We therefore conclude that more and more studies apply AI technologies to ECE. Note that although the number of publications shows a significantly increasing, the total number of studies of AI in ECE is still small.

Data aggregation is a crucial step in the literature review, which can be used to provide statistical analysis for collated research data and to create summarized data. We retrieve the aggregation type of publications from 2010 to 2022, as shown in Fig. 3. The results show that the related works are mainly reported in journals and conference proceedings. Specifically, there are more than 6000 publications and more than 1000 publications reported in journals and conference proceedings respectively. We notice that most publications of AI

[1] https://github.com/pybliometrics-dev/pybliometrics.

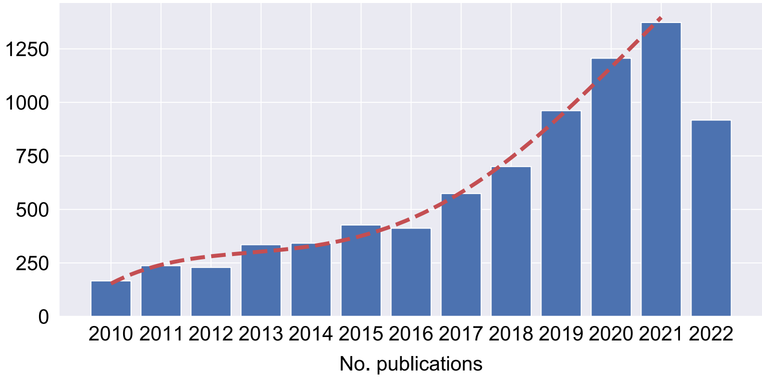

Fig. 2 The number of publications per year (from 2010 to 2022) on the topic of AI in ECE. The dashed red lines are the fit of the number of publications. Scopus database returned 9014 results until 10/10/2022. (Color figure online)

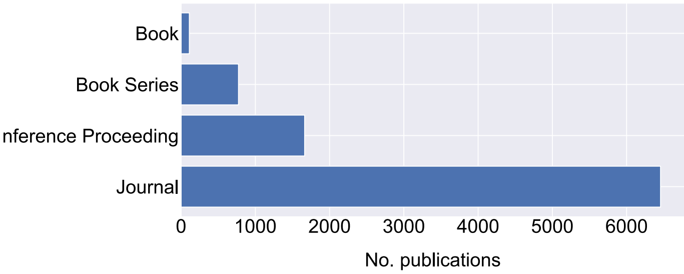

Fig. 3 Aggregation type of publications on the topic of AI in ECE (from 2010 to 10/10/2022)

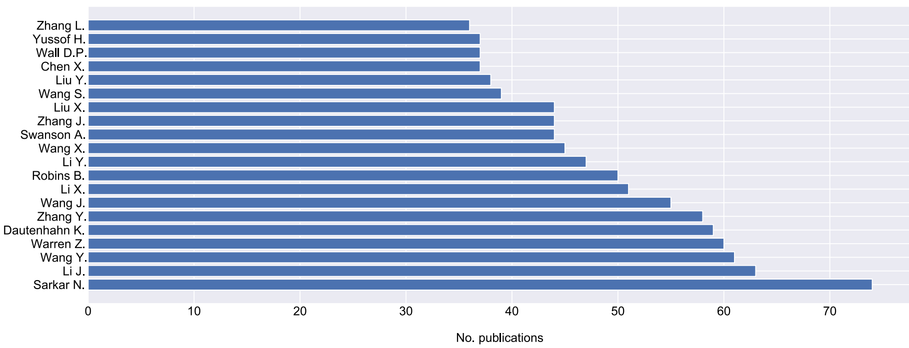

Fig. 4 Top 20 authors and their number of publications on the topic of AI in ECE (from 2010 to 10/10/2022)

in ECE are reported in journals for scientific theory presentation rather than technologies and academic exchange at conferences. We assume that current studies investigate AI in ECE at the level of scientific research rather than practical applicaitons, which is consistent with our conclusion in Sect. 4.1. To provide readers with a guideline for following the

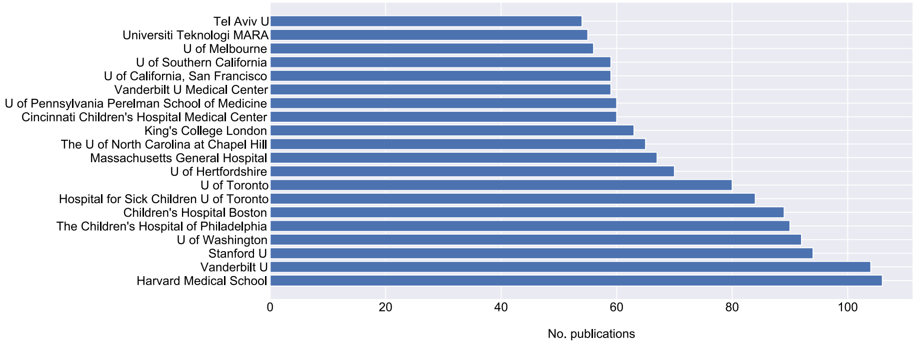

Fig. 5 Top 20 affiliations and their number of publications on the topic of AI in ECE (from 2010 to 10/10/2022)

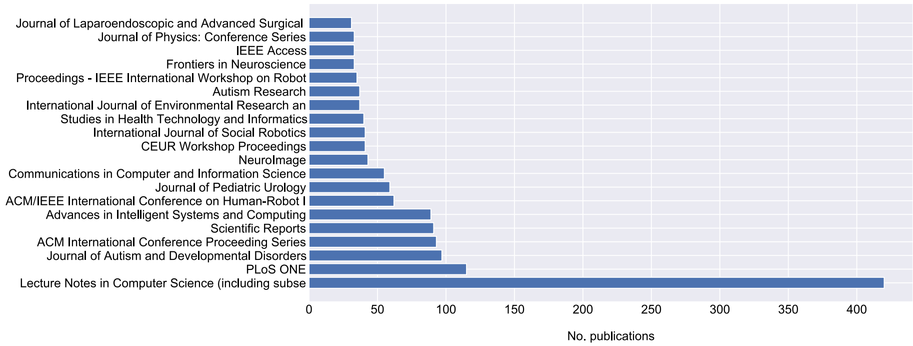

Fig. 6 The top 20 venues and their number of publications on the topic of AI in ECE (from 2010 to 10/10/2022)

studies from a researcher who focuses on ECE, we retrieve the publication's authors. The top 20 authors and their number of publications on the topic of AI in ECE are shown in Fig. 4. All these 20 authors published more than 30 studies on the related topic of AI in ECE. We notice that most of them focus on the applications of AI-based intelligent robots rather than AI in ECE. Currently, there are a few researchers who focus on AI in ECE.

Moreover, we retrieve the affiliations to reveal the top affiliations. The top 20 affiliations and their number of publications on the topic of AI in ECE are shown in Fig. 5. In particular, Harvard Medical School published the most articles which are more than 100. Vanderbilt University also published more than 100 articles. Importantly, most of these top 20 affiliations are medical schools or hospitals, including Harvard Medical School, The Children's Hospital of Philadelphia, Children's Hospital Boston, Hospital for Sick Children University of Toronto, Massachusetts General Hospital, Cincinnati Children's Hospital Medical Center, University of Pennsylvania Perelman School of Medicine, and Vanderbilt University Medical Center. The document source discovers the ways that share research results in a specific domain. There are several venues, including conferences and journals, where researchers share their studies with others and build their reputations. The top 20 venues and their number of publications on the topic of AI in ECE are shown in Fig. 6. The related studies of AI in ECE are basically published in the journals and conferences of

Fig. 7 The popular intelligent robots in ECE

the computer science domain such as the conferences and journals in ACM and IEEE society. In addition, there are many studies are reported in multidisciplinary and mega journals such as PLoS ONE, Scientific Reports, and IEEE Access.

3 Intelligent robots for ECE

Intelligent robots have demonstrated good performance in children-related areas, such as ECE. Huijnen et al. (2017a) present an overview of the studies about AI-based robots that are used in therapy and education for children with ASD. The results indicate that intelligent robots are possible valuable tools in the education or therapy of autistic children. Ismail et al. (2018) analyzed the applications of various robots for improving social and communication skills among autistic children. The PhD thesis (Haibin 2012) discussed the popular design approaches and issues of social robots for children, introduced several representative social robotics and reviewed several representative facial expression-based emotion recognition algorithms of social robotics. Furthermore, a robotic nanny was designed in a pilot study to evaluate whether the children liked the appearances and functions of the robotic nanny and collect the parent's opinions on the remote user interface designs. Results show that most children and parents express great interest in the robotic nanny and provide comparatively positive evaluations. In this section, we provide a comprehensive review of the existing studies of representative intelligent robots in ECE. The popular intelligent robots are shown in Fig. 7.

3.1 iRobiQ

iRobiQ, an advanced intelligent robot, is equipped with many functions such as broadcasting sound, facial emotion, fall protection, and collision protection. The previous studies on educational robots mainly focus on the preference of robot appearance (Koay et al. 2007), functions, the reaction of a robot (utterance and touching) (Austermann and Yamada 2008), the contents, and the effectiveness of educational robots. Especially, many studies have been actively conducted on iRobiQ. The findings show that children perceive intelligent robots as learning helpers and playmates (Hyun et al. 2010).

There are many studies that applied iRobiQ to investigate children's perceptions of AI-based things. Hyun et al. (2012) explored children's perception of iRobiQ, the assistive intelligent robot. The findings show that although children perceive iRobiQ as closer to a human than other artificial things, they perceive iRobiQ as a hybrid compound entity, and perceive a robot as an existence close to humans only when it performed functions similar to the functions of human cognition. In Han et al. (2015), iRobiQ is used to examine children's perceptions toward the computer- and robot-mediated augmented reality systems for interactive and participatory dramatic activities. Hyun and Yoon (2009) applied iRobiQ to investigate children's behavior when they were given free access to intelligent devices at kindergarten. The results demonstrate that children are capable of intelligent robot utilization under instructions. Hyun et al. (2010) investigated biological, mental, social, moral, and educational perceptions of children with iRobiQ. The results suggest that intelligent robots should be placed in the classroom for ECE.

Intelligent robots are educational tools with the potential to enhance language and literacy skills in children (Neumann 2020). There are many studies that applied iRobiQ to improve childhood language learning. Lee and Hyun (2015) developed language-intervention content on iRobiQ as a special education agent to promote language interaction for children with speech disorders. The results show that intelligent robots perform a significant effect in assisting speech disorders treatment. In Hsiao et al. (2015), iRobiQ was used as a language teaching/learning tool to improve children's reading ability and learning behavior. Fifty-seven children from prekindergarteners were divided into an experimental group of 30 children using iRobiQ and a control group of 27 children using a tablet-PC. The results show that the experimental group performs better reading ability than that of the control group.

3.2 NAO

NAO is an open and easy-to-handle intelligent humanoid robot platform with a comprehensive and functional design (Gouaillier et al. 2009). Ahmad et al. (2016) present a long-term study conducted at a school with twelve children by playing a snakes and ladders game with an NAO. The study investigated children's views on various adaptation behaviours such as emotion, memory, and personality of intelligent robots in education for maintaining and creating long-term engagement and acceptance. The results show that children reacted positively toward the use of intelligent robots in education. Rosi et al. (2016) investigate if an intelligent robot could improve the efficacy of a game-based, nutritional education intervention. The results show a significant increase in the nutritional knowledge of children involved in a game-based, single-lesson, educational intervention. Vrochidou et al. (2018) investigated the effectiveness of intelligent robots in ECE through an innovative game-based activity for teaching/learning numeracy. The results indicated that children were motivated by the presence of NAO and performed a better understanding of the mathematical concepts.

Ioannou et al. (2015) studied children's behaviour with NAO to explore how robots attract children's attention and interest. The results demonstrate that children show various interest in the particular behaviours of intelligent robots such as NAO dancing and interacting with NAO easily. Depešová et al. (2018) addressed the examples of implementing interesting solutions with NAO for teaching, particularly ECE. Teachers can apply NAO to improve ECE with desired solutions. In Alkhalifah et al. (2015), NAO is used to design an intelligent robot system that facilitates the kindergarten education process by providing quizzes to test the children's understanding. The system enables teachers to continuously review the student's progress through an application interface.

The existing studies indicate that intelligent robots are effective education agents for the therapy of children with ASD. In Suzuki et al. (2017), NAO is used to investigate whether the use of intelligent robot dancing can be applied to facilitate the dance therapy of children with ASD. The results show that NAO can be employed effectively in therapy for children with ASD. Amanatiadis et al. (2017) applied NAO to robot-assisted special education through specially designed social interaction games. The results demonstrated that robot-assisted treatment improves children's behaviour, and therefore an engagement of intelligent robots in special education is encouraged. The thesis Gao (2016) presents the improvements of NAO Robots in the education system. The experimental results show that the autism behaviour of the children with ASD in NAO-based education is greatly reduced than the normal class session. Most children with Down syndrome have not received special education. Jiménez et al. (2019) propose the use of the humanoid robot NAO for the education of children with Down syndrome. The operation of the Humanoid robot NAO with sensors such as tactile, cameras, and microphones attracts the children's attention to solve the issue that children with Down syndrome lose their attention very quickly, which builds interaction between robots and children. The results indicate that the use of an NAO would be a great improvement for the education of children with Down syndrome which differs from traditional education.

3.3 KASPAR

KASPAR is a child-sized humanoid robot that equips with minimal sensing capability and was capable of being controlled remotely for child-robot interaction, which is designed as a social companion to improve the behaviour of autistic children for simpler and more comfortable social interaction (Wood et al. 2017, 2021). Wainer et al. (2010) investigate whether children have difficulties communicating and engaging in social activities, and would perform more collaborative behaviours after playing and interacting with intelligent robots. The results suggest that children's intermediaries with KASPAR bring better entertainment and collaboration with a human. Similarly, Wainer et al. (2014) present a novel implementation of a collaborative game involving KASPAR playing games with autistic children. The results demonstrate the proof-of-concept of using an intelligent robot to encourage collaboration among autistic children. In Wainer et al. (2014), a pilot study in which a novel experimental setup involving a KASPAR participating in a collaborative was implemented and tested with autistic children. The results show that children perform more engagement in playing and better collaborative behaviours with their partners.

Huijnen et al. (2017b) present an overview to systematically describe intelligent robots in ECE and therapy interventions for autistic children in general and KASPAR in particular. Zaraki et al. (2018) presented an intelligent robot-based development of social skills and capabilities in children with ASDs as well as typically developing children. Specifically, a reinforcement learning algorithm with verbal expression of KASPAR's choice uncertainty is developed to facilitate understanding by children. The experimental results show that Kaspar only made a few unexpected associations, mostly due to exploratory choices, and eventually reached minimal uncertainty and all children expressed enthusiasm. Costa et al. (2013) investigated a novel scenario for robot-assisted play to increase body awareness, which teaches autistic children about identifying the human body. The results show that intelligent robots can be considered a tool for prolonging children's attention spans. In the further study, Costa et al. (2015) studied a human-robot interaction focusing on tactile interaction, in which autistic children interacted with KASPAR. The results show that autistic children spent increasing time on the intelligent robot through the appropriate physical interaction using KASPAR.

3.4 Keepon

Keepon is a small creature-like robot designed to conduct nonverbal interactions with children (Kozima et al. 2005, 2009). Costescu et al. (2015) investigated the role of Keepon in a cognitive flexibility task performed by children with ASD. The results show that children with ASD tend to enjoy interacting with Keepon. In Kozima and Nakagawa (2007), Keepon is placed in a playroom and tele-controlled, where children show a wide range of spontaneous actions such as speaking to Keepon. Kozima et al. (2007) applied Keepon to conduct a longitudinal observation of unconstrained child-robot interaction at a daycare center for autistic children. The results indicate that autistic children generally have difficulty in interpersonal communication, and are able to approach Keepon with a sense of curiosity and security.

Kozima and Nakagawa (2006) applied Keepon to explore the possible use of interactive robots in communication care for children, especially children with special needs. The children naturally and spontaneously showed various communicative actions to Keepon. Peca et al. (2016) investigated if children regard an unknown intelligent robot as a communicative partner through learning from a brief conversation between a human adult and Keepon. The results indicate that children perform a significantly higher level of initiations with the interactive robot than in the non-active robot condition.

3.5 AIBO

AIBO is a series of robotic dogs designed and manufactured by Sony, which increase children's motivation and offer a more joyful perception to children during the learning process. Batliner et al. (2004) applied AIBO to process children's speech, emotional speech, human-robot communication, cross-linguistics, and reading. Intelligent robots such as AIBO are used to analyze children's attitudes for interaction with morphological different devices in terms of appearance and behaviour (Bartlett et al. 2004). The results show that children are attached to the word 'dog' reflecting a conceptualization that robots look like dogs (in particular AIBO) and are closer to living dogs than other devices. Fior et al. (2010) examine how children regard an intelligent robot after a brief interaction. The results indicate that most children enjoy friendships with intelligent robots such as AIBO by showing positive affiliation and social activities. A suitable learning environment with a proper learning program is essential for children (Wei and Hung 2011). The results demonstrate that joyful learning systems with flexible, mobile and joyful intelligent robots are useful for ECE.

3.6 IROMEC

IROMEC is designed with a modular robot companion tailored towards engaging in social interaction for children with disabilities, which provides children with new opportunities to prevent isolation and develop new skills. The study (Van Den Heuvel et al. 2017a) explored the application of IROMEC for children with severe physical disabilities in rehabilitation and special education. The results show that the application of intelligent robots like IROMEC for children with severe physical disabilities is positive and worthwhile, but usability and feasibility are crucial. Similarly, Van Den Heuvel et al. (2017b) used the IROMEC robot to improve rehabilitation and special education for children with severe physical disabilities. The existing use cases of IROMEC provide the potential to support childhood playing with severe physical disabilities, especially movement functions, learning and applying knowledge, communication/interpersonal interactions and relationships.

Ferrari et al. (2009) investigated the role of IROMEC in therapy and education for children with special needs, and addressed the therapeutic and educational objectives related to autistic children. The results show that intelligent robots are helpful for children to learn new developmental skills. Robins et al. (2012) developed a novel set of ten scenarios for robot-assisted games for children with special needs. These scenarios are a meaningful extension of IROMEC for investigating how intelligent robots become social mediators from solitary to collaborative activities with peers and carers/teachers.

3.7 iCat

iCat was developed by the Dutch research firm Philips and designed to be a generic companion robotic platform for studying social human-robot interaction with mechanically rendered facial expressions (Breemen et al. 2005). iCat is generally used to interact with children by wearing a wireless sensor for measuring children's electrodermal activity. The results yield significant correlations regarding how children perceive the interaction and their emotions. Leite et al. (2012) investigated the children's interaction with iCat which recognises and responds to children's emotions. The findings suggest that iCat empathic behaviour affected positively children's cognition of intelligent robots. Shahid et al. (2010) investigated how children interact with intelligent robots, where iCat and a child collaborated to play a simple card guessing game. The results show that children enjoyed playing a game with iCat and felt happier afterwards.

Palestra et al. (2017) proposed an AI system for robot-assisted interaction based on a behavioural treatment protocol for autistic children, in which iCat is used to elicit specific behaviours in autistic children. The results show that a social robot as the mediator is successful in the robot-assisted treatment of autistic children. Kasimoglu et al. (2020) introduced iCat for techno-psychological distraction technologies to reduce children's anxiety and improve their behaviour during dental treatment. The results indicate that intelligent robots successfully mitigate dental anxiety and stress.

3.8 PARO

PARO is an interactive robot with a seal appearance (Sharkey and Wood 2014), which has five types of sensors of tactile, light, audition, temperature, and posture sensors. Cifuentes et al. (2020) applied PARO to a psychiatric ward of children and adolescents for relaxation and an improvement in communication. Crossman et al. (2018) provide the scientific demonstration that intelligent robots such as PARO are useful for improving children's mental health. The results show that PARO is useful to improve children's mood through a range of stressful circumstances, such as medical procedures and school assessments. Pipitpukdee and Phantachat (2011) use PARO to mitigate the behaviour problems of Thai Autistic children such as low motivation and communication problems. The results demonstrate that PARO could be applied to increase communication and motivation. Shibata and Coughlin (2014) conducted PARO in childhood activities and therapy for both cognitive and physical rehabilitation. The results show that PARO performs clear therapeutic effects on children, particularly those with cognitive impairments.

3.9 Probo

Probo is designed to be a natural interaction while employing human-like social cues and communication modalities (Goris et al. 2008, 2010). Chevalier et al. (2017) proposed specific strategies for human-robot interaction dialogues and interactions for school-aged autistic children. Vanderborght et al. (2012) applied Probo to provide robot-assisted therapy for autistic children. The results show that the social performance of autistic children improves when using the intelligent robot Probo as a medium for social storytelling than when a human reader tells the stories. Probo imitates children's faces to encourage children to notice facial expressions in a play-based game.

3.10 Other intelligent robots

There are also other intelligent robots that apply AI to ECE, such as PaPeRo (Osada et al. 2006), EngKey (Yun et al. 2011), and RUBI (Movellan et al. 2007).

PaPeRo is a popular intelligent robot because of its cute appearance and facial recognition system. Han et al. (2005) compared the effects of traditional media-assisted learning with the effects of robot-assisted learning. The results suggest that robot-assisted learning is more effective for children's learning concentration, learning interest and academic achievement than traditional media-assisted learning. Kawata et al. (2008) proposed a method to promote the intermixing of parents and children, and developed the network-based interactive child-watch system. Parents in remote locations could get detailed information about their children's activities and expressions when desired via asynchronous communication.

Engkey is a friendly and accessible avatar tele-education robot with a dumpy egg-shaped appearance that has been deployed in South Korean classrooms to teach students English via telepresence (Sharkey 2016). Kim et al. (2012) proposed a robot motion programming method by applying a three-level robot motion hierarchical structure and a gesture variation method. Children show great interest in learning English with Engkey.

RUBI was designed for accelerating the development of robots that interact with people (Movellan et al. 2007), which is generally used to be an intelligent sociable robot as a tool in ECE (Johnson et al. 2012). Movellan et al. (2009) used RUBI to improve children's vocabulary skills. The results show that RUBI conducts a significant improvement in the average vocabulary score of the children. Malmir et al. (2013) explored whether RUBI could autonomously data-mine the children's behavior and provide insights into the preferred activities by children. The results indicate that RUBI could apply the facial expression data to accurately predict the children's preference for different activities.

3.11 Discussion

The summary of these popular intelligent robots for ECE, including their specifications and the studies on these intelligent robots, are addressed in Table 2. Many intelligent robots have been applied in ECE. In general, the existing studies applied artificial intelligence technologies to these intelligent robots for better interaction with children, particularly children with interaction disorders such as ASD or Down syndrome. For example, deep learning-based computer vision is used to recognise the children's facial emotions and present facial emotions to children for building friendly interaction with children (Del Coco et al. 2017; Kamble and Dale 2021; Haibin 2012; Vanderborght et al. 2012; Malmir et al. 2013). In addition, many intelligent robots (Breemen et al. 2005; Hsiao et al. 2015; Osada et al. 2006; Goris et al. 2010) provide the function of facial emotion recognition and facial expressions. Furthermore, intelligent robots and artificial intelligence are used to improve childhood language learning and literacy skills in children (Neumann 2020). Intelligent robots and artificial intelligence technologies perform a significant effect in assisting speech disorders treatment and children's reading ability and learning behavior (Lee and Hyun 2015; Hsiao et al. 2015; Neumann 2020). To support the development of these AI technologies in ECE, these intelligent robots are generally equipped with the hardware of cameras, speakers and microphones. In summary, AI-based intelligent robots significantly contribute to ECE, particularly the education of children with interaction disorders.

Although intelligent robots and AI technologies have been applied to ECE, the applications of AI in ECE are still weak and need to be further investigated. The current studies on intelligent robots generally apply weak AI technologies such as the question–answer chatbot in ECE (Lee and Hyun 2015; Hsiao et al. 2015). Although intelligent robots are perceived by children as closer to a human than other artificial things, they perceive intelligent robots as a hybrid compound entity and perceive a robot as an existence close to humans only when it performed functions similar to the functions of human cognition (Hyun et al. 2012). The AI-based intelligent robots are still far to provide children with a better interaction even the human-like cognition for ECE. Therefore, intelligent robots need to integrate state-of-the-art AI technologies in ECE, such as the AI-powered language model ChatGPT, to generate human-like interaction with children. In summary, intelligent robots should apply state-of-the-art AI technologies to improve the AI applications in ECE and extend novel applications to assist ECE, particularly the education of children with interaction disorders.

4 Key AI technologies in ECE

Many AI technologies have been widely applied in ECE. In this section, we review the studies of the main AI technologies including data mining, machine learning, deep learning, virtual reality, computer vision, and natural language processing in ECE.

Table 2 The summary of the popular intelligent robots for ECE, including their specifications and the related studies

AI Robots	Studies	Developers	Hardware	Features	Remarks
iRobiQ	Hyun and Yoon (2009), Hyun et al. (2012), Han et al. (2015), Neumann (2020), Lee and Hyun (2015), Hsiao et al. (2015), Kasimoglu et al. (2020)	Yujin Robot	Cameras Speaker Touch screen	Emotions Speech Actions	5 facial expressions, intelligent avoiding obstacles for house surveillance, natural language process
Probo	Goris et al. (2008, 2010), Chevalier et al. (2017), Vanderborght et al. (2012)	Vrije Universiteit Brussel	Digital cameras Microphones Touch sensors	Speech Emotions Gestures	A research platform to study cognitive human-robot interaction
NAO	Ahmad et al. (2016), Ioannou et al. (2015), Vrochidou et al. (2018), Alkhalifah et al. (2015), Depešová et al. (2018), Rosi et al. (2016), Gao (2016), Suzuki et al. (2017), Amanatiadis et al. (2017), Jiménez et al. (2019)	Aldebaran Robotics	Cameras Speaker Microphone	Walk and dance Talk Play games	An autonomous, programmable humanoid robot used in numerous academic institutions for education
KASPAR	Wood et al. (2017, 2021), Wainer et al. (2010, 2014), Huijnen et al. (2017b), Zaraki et al. (2018), Costa et al. (2013, 2015)	University of Hertfordshire	Cameras Tactile sensors	Speech Emotions Actions	A child-sized humanoid robot specifically developed for childhood interaction
Keepon	Kozima et al. (2005, 2007, 2009), Costescu et al. (2015), Kozima and Nakagawa (2006), Peca et al. (2016)	NICT	Cameras Microphone	Dance mode Touch mode	Keepon is a small robot designed to study childhood interaction
AIBO	Batliner et al. (2004), Bartlett et al. (2004), Fior et al. (2010), Wei and Hung (2011)	Sony	Cameras Microphone Speaker	Object detection SLAM Self-charge	An AI-based robot, which is used extensively in education and academia
IROMEC	Van Den Heuvel et al. (2017a, b), Ferrari et al. (2009), Robins et al. (2012)	IROMEC	Microphone Screen Other sensors	Emotions Sound recognition Actions	An interactive social mediator robot to be a playmate for children with disabilities
iCat	Kasimoglu et al. (2020), Breemen et al. (2005), Shahid et al. (2010), Leite et al. (2012), Palestra et al. (2017)	Philips	Cameras Speakers Stereo microphones	Face recognition Facial expressions Control devices	A companion robotic platform for studying social human-robot interaction

Table 2 (continued)

AI Robots	Studies	Developers	Hardware	Features	Remarks
Paro	Pipitpukdee and Phantachat (2011), Sharkey and Wood (2014), Shibata and Coughlin (2014), Crossman et al. (2018), Cifuentes et al. (2020)	AIST	Microphone Multimodal sensors	Speech Voice sampling Heating system	An advanced interactive robot with cute seal shape for children therapeutic

Data mining is a popular AI technique that has been widely applied in ECE. Data mining technologies is used to extract useful information from a vast amount of data, which discover new, accurate, and useful patterns in the data. Chang (2007) applied a data mining approach to find hidden knowledge and obtain useful information as a reference for decision-making and evaluation in children's healthcare. Subsequently, a decision tree is used to classify children's developmentally-delay levels according to their physical illness. This study identifies which type of illness causes certain types of delays by the decision tree. The results provide healthcare personnel with important references during diagnosis and evaluations. Al-Diabat (2018) analyse the autism behavioural characteristics data and investigate fuzzy rule-based data mining models to forecast children's autistic symptoms. The results demonstrate that the fuzzy data mining model with regard to predictive accuracy and sensitivity rates outperform the other rule-based data mining models.

Leroy et al. (2006) applied the data mining technologies of decision trees and association rules to develop a digital library of coded video segments that contain data on the appropriate and inappropriate behaviour of autistic children in different social scenarios. The results show that therapy is effective in reducing inappropriate behaviour and increasing appropriate behavior. Data mining technologies such as classification algorithms are widely applied to predict childhood obesity. Abdullah et al. (2016) investigate the classification of childhood obesity for children in Malaysia. The classification technologies, Bayesian Network, Decision Tree, Neural Networks, and SVM were implemented and compared on the data sets. The results show that the classifiers of J48 and SMO outperform the other two classifiers for predicting childhood obesity. Zhang et al. (2009) compared data mining methods with logistic regression in childhood obesity prediction. The results show that SVM and Bayesian algorithms outperform other algorithms for predicting overweight and obese children on the Wirral database.

In Momand et al. (2020), a data mining approach is proposed to predict the malnutrition status of children in Afghanistan. The results show that the proposed data mining approach robustly predict the malnutrition status based on clinical sign and anthropometric parameters of Afghan children. Krotova et al. (2020) applied data mining methods to develop a diagnostic model for diabetes mellitus complications, which explores the possibility of diagnosing diabetic polyneuropathy by using machine learning methods. Interestingly, El Afandi (2013) investigate if a relationship exists between the occurrence of allergies in children and daily upper-air observations (e.g., temperature, relative humidity, dew point, mixing ratio) and air pollution (e.g., particulate matter, sulfur dioxide, nitrogen dioxide, carbon monoxide, and ozone). The results show that the prevalence of allergies increased over the last few years. Monitoring upper-air observation and air pollution data over time is a reliable method for predicting outbreaks of allergies among elementary school children, which enables parents and school nurses to implement effective precautionary measures.

Yue et al. (2018) designed an intelligent system to obtain video clips in a kindergarten classroom and leverage emotional data to portray the mental states of children. Gathering and analyzing children's emotional features by data mining methods reached important conclusions, which are beneficial to developing educational policy and teaching practice. Diagnostic information on the presence of infection, severity and aetiology (bacterial versus viral) is crucial for the appropriate treatment of childhood pneumonia. The work (Naydenova et al. 2016) explores a suite of data mining tools to facilitate automated diagnosis through quantifiable features. The results indicate that machine learning tools are successfully used for the multi-faceted diagnosis of childhood pneumonia in resource-constrained settings, compensating for the shortage of advanced equipment and clinical expertise.

Here, we review the studies of machine learning in ECE. Machine learning is the development of discovering algorithms that permit machines to learn relations without human intervention from the existing datasets. To find appropriate classifiers, Delavarian et al. (2011) compare 16 linear and non-linear classifiers to distinguish and diagnose children with many similar symptoms and different behavioural disorders such as ADHD, depression, and anxiety. The results show that the nearest mean classifier was selected as a relevant classifier by categorizing 96.92% of the samples correctly. The article (Lin et al. 2020) presents a conversational platform and curriculum designed to facilitate children's understanding of machine learning concepts. The results indicate that the conversational platform increased engagement during learning and the novel visualizations make machine-learning concepts understandable for children. Hitron et al. (2018) studied if 10–12 years old children understand machine learning concepts through the experience with a digital stick-like device. The results indicate that children are able to understand basic machine learning concepts and even apply these concepts to daily life.

Visual and audio data are gathered during the child-robot interaction and processed towards deciding an engaged state of children by AdaBoost decision tree (Papakostas et al. 2021). Hagenbuchner et al. (2015) develop machine learning models for predicting activity types in preschool-aged children. The results contribute to the evidence supporting the application of machine learning approaches to accelerometry data analysis in children. Ahmadi et al. (2018) develop machine learning models to automatically identify the physical activity types in ambulant children with Cerebral palsy. The random forest and support vector machine classifiers consistently outperform the binary decision tree classifiers. The results demonstrate that machine learning approaches with accelerometer data processing are feasible for identifying children with Cerebral palsy.

Rasheed et al. (2021) use machine learning technologies to examine the EEG data for predicting failure in the early years of school. The combination of the EEG data with sociodemographic and home environment variables can increase the specificity. Carpenter et al. (2016) apply machine learning tools to the PAPA data for identifying subsets of PAPA items, which could be developed into an efficient, reliable, and valid screening tool to assess the possibility of children with anxiety disorders. The machine learning approaches identify children for both generalized anxiety disorder and separation anxiety disorder with an accuracy of over 96%. A supervised machine-learning method (Crippa et al. 2015) is developed to correctly discriminate preschool children with ASD from the typically developing children by kinematic analysis of a simple reach-to-drop task. The findings offer insight into a possible motor signature of ASD that is useful for identifying a well-defined subset of patients and reducing the clinical heterogeneity within the broad behavioural phenotype. Liu et al. (2016) proposed the face-scanning patterns to identify children with ASD by an SVM classifier with data-driven feature extraction. Developing the AI-aid early detection and diagnosis system is helpful to screen and diagnose ASD in children.

McGinnis et al. (2018) proposed a new approach for diagnosing anxiety and depression in children, in which wearable sensors are used to monitor the participant's motion during the period. The experimental results show that the approach performs a diagnostic accuracy of 75%. Similarly, McGinnis et al. (2019) proposed a new approach to identify children with internalizing disorders using an instrumented 90-s mood induction task. The data from a single wearable sensor during a 90-s fear induction task and a machine learning approach are proposed to fulfil this need. This work provides an important step for overlooked children to both mitigate their distress and prevent subsequent comorbid emotional disorders and additional negative sequels. Su et al. (2020) develop machine learning models to predict suicidal behavior among children and adolescents based on their longitudinal clinical records, and determine short- and long-term risk factors. The findings demonstrate that routinely collected electronic health records can be used to develop accurate predictive models for preventing suicide risk among children and adolescents.

Deep learning has been widely applied in various applications, including ECE. In this section, we review deep learning-based studies in ECE. Di Nuovo et al. (2018) proposed a novel deep-learning neural network to automatically estimate if the children focus on the robot during a therapy session. The results show that CNN-based approaches significantly outperform the benchmark algorithms for estimating children's attention. Rudovic et al. (2018) applied deep learning models to the task of automated engagement estimation by using face images of children with autism. The authors claim that it is the first study to investigate the effects of individual and cultural differences in children with autism in the context of deep learning performed directly from face images. Kim et al. (2015) developed a deep learning-based system of a video question and answering game robot for early childhood interactive education in real-world environments. She and Ren (2021) proposed a chat robot with the use of a deep neural network model as the generative conversational agent, which generates meaningful and coherent dialogue responses to improve the context sensitivity of early children.

In Liu et al. (2018), a deep learning approach was applied to detect premature ventricular contractions in children automatically. The AI-aided diagnosis model achieved high accuracy while sustaining stable performance. Lempereur et al. (2020) study the deep learning-based method to detect gait events in children with gait disorders. A long short-term memory recurrent neural network, called DeepEvent, is proposed to detect children's gait disorders. The results show that DeepEvent outperforms the existing well-known approaches for detecting children's foot strikes and foot-off. Kumar and Senthil (2021) used deep learning classifiers to predict children's behavior by considering their emotional features. Chatzimichail et al. (2010) present an effective deep neural network to predict persistent asthma in children. The results demonstrate that deep neural networks predict the asthma of children successfully. The interesting study (Yu et al. 2021) investigates the associations between trees and grass presence with childhood asthma prevalence using deep learning-based image segmentation. The results indicate a role of vegetation in the association between greenness exposure and childhood asthma. The finding provides valuable information to reveal the effects of different green vegetation on childhood asthma and the underlying mechanisms.

In addition, virtual reality, computer vision, and natural language processing are the other mainstream AI technologies that are applied in ECE. In this section, we mainly review the existing works in aspects of virtual reality, computer vision, and natural language processing.

In the early works, the article (McComas et al. 1998) provided an overview of virtual reality for children with disabilities. This work investigates the benefits of VR for children with disabilities and explores how to apply VR to the needs of children with disabilities. The results show that VR provides disabled children with practice skills. Gershon et al. (2004) conducted VR as a distraction for children with cancer to reduce anxiety and pain associated with an invasive medical procedure. The results found that using VR distraction reduces the pain and anxiety of children compared to the no-distraction scenes. The findings suggest that VR is a useful tool for distraction during painful medical procedures. Parsons and Cobb (2011) addressed the state-of-the-art of VR technologies for autistic children to assess how VR can be used in practice. Arane et al. (2017) investigate how VR work in reducing pain and anxiety in children patients. The preliminary results show that VR is effective in reducing the pain and anxiety children patients experience compared with standard care or other distraction methods.

Foley and Maddison (2010) assess active video games to increase energy expenditure and physical activity behaviour in children. The findings indicate that playing active games results in greater energy expenditure compared with nonactive video games, and is approximate to moderate-intensity physical activity. VR was applied to be a promising and motivating approach to practice and rehearse social skills for children with ASD (Didehbani et al. 2016). The findings suggest that VR offers an effective treatment for improving social impairments in children with ASD. Jyoti and Lahiri (2019) developed a VR-based joint attention system of varying difficulty levels coupled with a hierarchical prompt protocol for children with ASD. The results indicate that the VR-based joint attention system was able to estimate the joint attention level of a group of children with ASD.

Josman et al. (2008) investigated whether children with ASD are capable of learning the skills needed to cross a street safely via a street-crossing VR and whether these skills can be transferred to real life. The experimental results show a significant improvement in children with ASD crossing a real-street setting after learning and considerable improvement in the virtual street. Similarly, Schwebel and McClure (2010) use VR to train children in safe street-crossing skills. The results demonstrate the efficacy of VR to train child pedestrians in safe street crossings. A VR system is applied to enhance emotional and social skills for children with ASD (Ip et al. 2018). The study demonstrated the clear feasibility of VR for enhancing the emotional and social skills of children with ASD.

Computer vision approaches are mainly applied to recognize children's faces for ECE. Del Coco et al. (2017) demonstrate that computer vision-based approaches for facial feature analysis can be used to understand emotional behaviours for the assessment and diagnosis of ASD in preschool children. Dongming et al. (2020) introduced a face-tracking pan–tilt–zoom solution with an intelligent robot to track children's faces and record videos in ECE. The convolutional neural network and k-nearest neighbour classification are applied to recognize children's faces. Kamble and Dale (2021) addressed the various face recognition technologies using different classifications in children. The results show that the approaches of machine learning and deep learning can be used to track facial changes in childhood with remarkable recognition accuracy. Xia et al. (2017) studied smile detection across the difference between children and adults. The state-of-the-art transfer learning methods are applied to the discrepancy in the well-known deep neural networks of AlexNet and ResNet. The results demonstrate the effectiveness of the proposed approach to smile detection across such a difference.

Druga et al. (2017) investigate how children perceive natural language processing by exploring children's interaction with the agents of Amazon Alexa, Google Home, Cozmo, and Julie Chatbot. This work suggests a series of design considerations for future child-agent interaction from voice/prosody, interactive engagement and facilitating understanding. Shahi et al. (2021) applied natural language processing models to detect child physical abuse. The results indicate that deep learning-based natural language processing for clinician judgement improves the recognition of physical abuse.

AI curriculum for children is an interactive and playful manner through engaging AI projects such as recognizing faces, VR training, and language learning. Children could have a basic understanding of AI concepts with an AI curriculum. Brownlee and Berthelsen (2006) provide a conceptual framework by analysing the current studies on epistemological beliefs and tertiary learning. The framework can be used in childhood teachers' education programs/curricula to explore how teachers implement AI concepts in ECE.

Williams et al. (2019a) developed an AI platform (PopBots) for designing an AI curriculum in ECE, where preschool children interact with social robots to learn basic AI concepts. In the PhD thesis (Williams et al. 2019b), Williams explores how children explore and create with AI, and how the activities influence children's perceptions of AI. Specifically, PopBots is used to develop a novel developmentally appropriate Preschool-Oriented Programming curriculum. The experimental results show that the social robot as a learning companion and programmable artefact is effective in helping children understand basic AI concepts. In addition to the AI curriculum at preschool, family education about AI is also crucial. Unlike unified childhood education in classes, family education is more flexible and targeted. Jin (2019) studies the effects of AI on childhood family education. The results show that AI could help to provide better family education for children.

4.1 Discussion

We summarize the key AI technologies in ECE in Table 3, including the studies of AI technologies in ECE and their specific methods and applications. Data mining technologies are generally used to analyse the data and predict the potential issues during the age of early childhood education and provide insightful recommendations for designing personal education and childcare. For example, data mining technologies were used to extract useful information from the behavioural characteristics data (Al-Diabat 2018), the digital library of coded video (Leroy et al. 2006), the occurrence of allergies in children and daily upper-air observations (El Afandi 2013) and then decision tree (Leroy et al. 2006; Chang 2007), fuzzy data mining models (Al-Diabat 2018), and classification algorithms (Abdullah et al. 2016; Zhang et al. 2009) are used to detect/predict children's symptoms and design personal education and childcare. Machine learning technologies developed algorithms [e.g., AdaBoost (Papakostas et al. 2021), random forest (Ahmadi et al. 2018)], support vector machine (Liu et al. 2016) to identify children's activities such as attention (Papakostas et al. 2021), failure (Rasheed et al. 2021), anxiety disorder (Carpenter et al. 2016; McGinnis et al. 2018), ASD (Crippa et al. 2015; Liu et al. 2016), suicidal behavior (Su et al. 2020). Note that although data mining and machine learning in ECE have a few overlaps of data, there are a considerable number of differences between them. Data mining technologies aim to extract useful information from a vast amount of data and discover useful patterns in the ECE data such as interaction data. Machine learning develops algorithms to learn relations from the existing ECE datasets.

Deep learning technologies generally train neural networks on datasets to estimate association for ECE. For example, deep neural networks are applied to estimate children's attention (Di Nuovo et al. 2018; Rudovic et al. 2018; Jyoti and Lahiri 2019), develop video question-answer games (Kim et al. 2015) and conversational agents (She and Ren 2021) for ECE. In addition, virtual reality has been applied in the practical education of children with disabilities (McComas et al. 1998), reduce anxiety of autistic children (Gershon et al. 2004; Parsons and Cobb 2011; Arane et al. 2017; Didehbani et al. 2016), develop children's activity (Foley and Maddison 2010), practice skills (Schwebel and McClure 2010; Ip et al. 2018). Finally, computer vision and natural language processing are used to recognize children's faces and children's speech respectively to provide interactive information for ECE.

Although AI technologies have been applied to early childhood education, the current studies of AI in ECE still have various open issues that need to be further investigated. First, AI technologies have not been investigated in many ECE tasks. For example, using data mining and machine learning technologies to discover the proper learning ways for

Table 3 The summary of AI technologies in ECE, including the studies, their methods, and their specific applications

AI technologies	Studies	Methods	Applications in ECE
Data mining	Leroy et al. (2006), Chang (2007), Zhang et al. (2009), El Afandi (2013), Naydenova et al. (2016), Abdullah et al. (2016), Yue et al. (2018), Al-Diabat (2018), Momand et al. (2020), Krotova et al. (2020)	Fuzzy data mining	Detect autistic symptoms
		Logistic regression, SVM	Behavioral therapy
		Bayesian algorithm	Predict allergies
		Decision tree	Predict childhood obesity/overweight
Machine learning	Delavarian et al. (2011), Hagenbuchner et al. (2015), Crippa et al. (2015), Liu et al. (2016), Carpenter et al. (2016), Hitron et al. (2018), Ahmadi et al. (2018), McGinnis et al. (2018, 2019), Lin et al. (2020), Rasheed et al. (2021), Papakostas et al. (2021)	AdaBoost decision tree	Machine learning concepts
		Neural networks	Predicting activity types
		Random forest, SVM	Predicting suicide
			Diagose anxiety and depression
Deep learning	Di Nuovo et al. (2018), Rudovic et al. (2018), Kim et al. (2015), She and Ren (2021), Liu et al. (2018), Lempereur et al. (2020), Kumar and Senthil (2021), Chatzimichail et al. (2010), Yu et al. (2021)	Deep neural networks	Estimate children's attention
		Image segmentation	Detect premature
		Cascaded convolutional networks	Detect gait disorders
			Predict persistant asthma
Virtual reality	McComas et al. (1998), Gershon et al. (2004), Parsons and Cobb (2011), Arane et al. (2017), Foley and Maddison (2010), Didehbani et al. (2016), Josman et al. (2008), Schwebel and McClure (2010), Ip et al. (2018), Strickland et al. (1996), Strickland (1996)	VR-based system	Reduce pain & anxiety
			Improve energy expenditure
			Practice emotional & social skills
Computer vision	Xia et al. (2017), Del Coco et al. (2017), Dongming et al. (2020), Kamble and Dale (2021)	Convolutional neural network & k-nearest neighbor classification	Face recognition and tracking
		Transfer learning	Smile detection
			Emotion recognition
Natural Language Processing	Druga et al. (2017), Shahi et al. (2021)	NLP models	Exploring children's interaction
			Detect children's physical abuse

various children, and using virtual reality and computer vision to design interesting AI programs for ECE. Furthermore, the current studies generally apply AI technologies to ECE at the level of scientific research. However, the ECE need more AI educational tools to show children visual AI concepts and applications, particularly interactive and practical AI educational systems. Second, most current studies applied typical and outdated AI technologies to ECE. We assume that the researchers in this domain usually do not follow state-of-the-art AI technologies. Therefore, advanced AI technologies such as ChatGPT need to be further investigated in ECE.

Finally, datasets are generally crucial for current AI technologies, particularly data-driven AI approaches such as deep learning. The available datasets are scarce since the useful data in ECE is hardly collected. It is significantly hard to collect quality data from children, and the data in ECE is generally sparse even untrustworthy. Therefore, data mining technologies are crucial to extract useful and large-scale data and build various datasets for supporting AI applications in various ECE tasks. We summarize the used datasets in these studies of AI in ECE, as shown in Table 4 where we addressed the dataset information.

5 Challenges and trends

Research trends and challenges are crucial for researchers to find interesting ideas. We aim to provide organized insights for the future development of ECE. In this section, we analyse the research trends and discuss the open challenges for shaping future research via bibliometric analysis. We retrieve the publication for discovering and demonstrating the trends of the key AI technologies in ECE.

5.1 Challenges

Although AI technologies have been widely applied in ECE, current studies generally use weak AI technologies in ECE. The AI technologies in ECE need to be further developed. There are many challenges to the further development of AI technologies in ECE. In this section, we discuss the challenges of the key AI technologies in ECE, including the challenges of data mining, machine learning, deep learning, and the challenges towards educators.

5.1.1 Challenges for data mining in ECE

Although data mining technologies have been applied in ECE, there are still many open challenges (Baker 2019).

- First, the transferability of the data mining model is a common challenge, which transfers the data mining models for various learning systems in ECE, e.g., the mentioned issues in Chang (2007) and Krotova et al. (2020).
- Second, the durability of the data mining model is a challenge for the different children in different years (Yue et al. 2018).
- Third, the generalizability of data mining is a significant challenge. The current data mining models have to be rebuilt basically from scratch for various different children learning systems in ECE (Al-Diabat 2018).

Table 4 The summary of the datasets used in the studies of AI technologies in ECE, including the studies, topics, AI technologies, and dataset information

AI tech	Datasets	Methods	Dataset information
Data mining	Medical records (Chang 2007)	Decision tree	605 pieces of developmentally-delayed children data
	AQ-10-child (Al-Diabat 2018)	FURIA	Autism behavioural characteristics data contains 252 No-ASD instances and 257 ASD instances
	SEGAK data (Abdullah et al. 2016)	SVM, etc	4245 childhood obesity data from 153 schools
	Wirral child database (Zhang et al. 2009)	SVM, etc	16,653 children with 56 attributes for each sample including weight, height, age and sex
	Medical records (Krotova et al. 2020)	SVM	3204 children suffering from type 1 diabetes, including age, height and weight,etc
	Upper-air data and health records (El Afandi 2013)	Binary logistic regression	168,825 children with occurrence of allergies and upper-air observations
	Emotional face (Yue et al. 2018)	k-means	14,049 sets of data, including 38 children in 4 courses and each lasting 30 min, covering 7 expressions
	Health records (Naydenova et al. 2016)	Random forest,etc	780 children diagnosed with pneumonia and 801 age-matched healthy controls
Machine learning	Behavioral disorders (Delavarian et al. 2011)	16 classifiers	306 children, 70 ADHD, 36 conduct disorder, 54 anxiety disorder, 38 depression, 34 comorbid depression and anxiety and 74 normal children
	Visual and audio (Papakostas et al. 2021)	AdaBoost	819 samples with 11 features for each sample during the child-robot interaction, including 99 engaged samples, 720 not engaged samples
	Accelerometer data (Hagenbuchner et al. 2015)	NNs	Accelerometer data of 12 activities including five activity classes (walking, running, etc) by 11 children in preschool
	EEG data (Rasheed et al. 2021)	K-NN	EEG data from 96 children at 8 years old
	Psychiatric assessment (Carpenter et al. 2016)	decision tree	diagnostic parent-report for assessing psychopathology in 2 to 5 years old children
	Activities (McGinnis et al. 2018, 2019)	K-NN logistic regression	wearable sensor data included 63 children (57% girls) with anxiety and depression
	Health records (Su et al. 2020)	logistic regression	41,721 childhood records within the Connecticut Children's Medical Center from 2011 to 2016

Table 4 (continued)

AI tech	Datasets	Methods	Dataset information
Deep learning	Video data (Rudovic et al. 2018)	CNN	audio-visual and autonomic physiological recordings of children in a robot-assisted education
	Cartoon video Q &A dataset (Kim et al. 2015)	CNN & RNN	1232 min and 183 episodes cartoon video, approximately 1200 question & answer pairs
	Dialogue (She and Ren 2021)	LSTM RNN	352,256 dialogue data between children and their parents, teachers, and friends
	ECG data (Liu et al. 2018)	CNN	Over 30,000 normal controls and around 1200 PVC cases of children
	3D gait (Lempereur et al. 2020)	LSTM RNN	10,526 foot strike (5247 left and 5279 right) and 9375 foot off (4654 left and 4721 right) from 226 children
Others	Childhood smile (Xia et al. 2017)	Adap. networks	17,517 images of children under 5 years old, including 6171 training, 3086 for validation, and 8260 for test
	Trauma data (Shahi et al. 2021)	DNN and NLP	abused children and non-abusive trauma children

5.1.2 Challenges for machine learning in ECE

The technical challenges for machine learning in ECE mainly involve the data and models.

- Overfitting of training data is a common challenge for machine learning in ECE when data is massive amounts of noisy and biased data, which can generally be solved by removing outliers data and longer training time (Rasheed et al. 2021; McGinnis et al. 2018, 2019).
- The absence of good-quality data in ECE is a current challenge for machine learning since it is hard to collect good-quality data from young children (Papakostas et al. 2021; Hagenbuchner et al. 2015). The operation of removing outliers, filtering missing values, and removing unwanted features can be used for data preprocessing.
- Explainability and accountability are two major issues of using machine learning in education (Razaulla et al. 2022; Webb et al. 2021). Explainability is described as the ability to understand and explain "in human terms" what is happening with the model. Accountability refers to the ability to explain and justify methods, actions and decisions.

5.1.3 Challenges for deep learning in ECE

Although deep learning has proven remarkable performance in ECE, its open challenges are also well-known (Li et al. 2022).

- A well-known common challenge of deep learning in ECE is the trustworthiness of deep learning. The results of black box models in deep learning are usually unknown to the trustworthy.
- Unsupervised/semi-supervised learning with a few labelled data is a reasonable approach and a significant challenge as well. Collecting and labelling large-scale data for supervised learning is a significant challenge that is even harder than collecting large-scale (Kim et al. 2015; Xia et al. 2017). Especially, there is a lack of labelled large-scale data in ECE.
- The state-of-the-art deep learning models generally require various computing costs and powerful GPUs for the iterative process (Li et al. 2022). The optimization of deep learning models with smaller sizes for less computing cost is a difficult challenge (Rudovic et al. 2018; Chatzimichail et al. 2010).
- Establishing a clear interpretable model is a significant challenge in ECE (Li et al. 2022). Current deep learning models are hard to be explained how they generate specific results. Interpretable techniques such as rule-based approaches, linear regression and tree-based algorithms could be fit to the interpretability in ECE (Delavarian et al. 2011; Su et al. 2020).

5.1.4 Challenges for other AI technologies in ECE

- Although other AI technologies have been applied in ECE, there are still certain challenges that need to be investigated. For example, one of the biggest challenges faced by virtual reality in ECE is the lack of content (Jyoti and Lahiri 2019; Ip et al. 2018).

However, developing VR content can be very expensive, which is a significant issue for ECE.

- The challenges of natural language processing in ECE are mainly data- and semantic-related (Druga et al. 2017). In particular, preparing high-quality data from children is a challenging issue. The semantic meaning of words from children is another common challenge for natural language processing in ECE (Shahi et al. 2021). In summary, most of the challenges of AI technologies in ECE are due to data quality such as sparsity, diversity and dimensionality.

5.1.5 Challenges towards educators

To date, various funds have been invested in AI technologies to equip schools with educational technology tools, but the vast majority of teachers do not use AI technologies in meaningful ways National Education Association and others (2008) and Office of Technology Assessment (1995). Only a few teachers allow students to use educational technology tools to solve problems, analyze data, present information graphically, or participate in distance learning (US Department of Education 2003). Large-scale studies have shown a significant increase in achievement scores of students using technology as a learning tool (Lei and Zhao 2007). The studies (Dani and Koenig 2008; Schroeder et al. 2007; Songer 2007) demonstrate that the use of AI technologies has a positive influence on a wide variety of student learning, including the understanding of science concepts and the development of scientific reasoning skills.

Even though there have been available educational AI technologies tools in the classroom, the integration of AI technologies in ECE is still challenging for teachers. With the use of AI technologies, teachers can prune curriculums and provide personalized learning options. Guzey and Roehrig (2012) integrated educational technology into secondary science teaching to develop the foundation for understanding teachers' use of technology. The findings demonstrate that all the participating teachers were motivated to use AI technology in their teaching. Many educators have brought AI concepts into ECE. We summarize four basic things that educators should know.

- Educators need a basic understanding of AI concepts.
- AI technologies are advancing rapidly that teaching curricula are irrelevant and lack proper AI instruction.
- Children are intimately familiar with AI-driven technology. Teachers can help children understand AI applications by connecting AI concepts to products.
- Coding is the baseline of AI instruction but not the goal.

Aside from the classroom and children's experience, AI can be used to improve the quality of education by empowering childhood practitioners. For example, AI technologies could be used for automating standardized procedures, gaining insights from data analytics, or providing AI-based professional development programs. AI educational technologies provide benefits compared to traditional education, including inspiring students' motives for creative activities (Prentzas 2013), assisting teachers to provide students with personalized self-adaptive learning (Xu 2020) and remove repetitive tasks and value-add to meaningful teaching tasks such as interactions with children. Therefore, using AI technologies to develop programs, curricula, and design novel meaningful teaching tasks to meet the requirement of ECE is a big challenge for educators even parents in the AI era. Finally, we

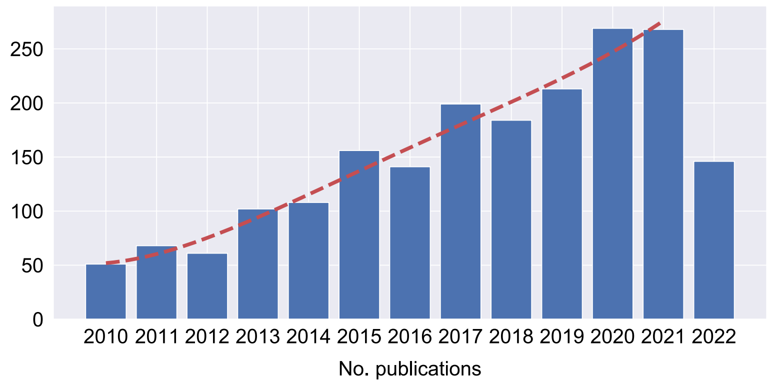

Fig. 8 The number of publications per year (from 2010 to 2022) on the topic of intelligent robots in ECE. The red dashed line is the cubic polynomial fit of the number of publications. Scopus database returned 2169 results until 10/10/2022. (Color figure online)

assure that the role of teachers will never be replaced by AI. The human element is crucial in ECE. Students do not be able to learn purely through AI-assist.

5.2 Trends

In this section, we analyse the trends of AI in ECE from the aspects of intelligent robots and AI technologies by bibliometrics.

5.2.1 Intelligent robots

Intelligent robots have demonstrated good performance in ECE. In particular, many commercialized robots (see Fig. 7) have been widely applied in ECE. We retrieve the literature on intelligent robots in ECE with the keywords by the search code of title-abs-key ((”robot” OR ”robots”) AND (”early childhood education” OR ”autism” OR ”autism spectrum disorder” OR ”ASD” OR ”preschool” OR ”kindergarten”)). The number of publications over the years is shown in Fig. 8. The number of publications on the topic of intelligent robots in ECE shows a significantly increasing trend. Although more and more works apply intelligent robots to ECE, current intelligent robots generally integrate weak AI even non-AI (computer-based learning systems). We conclude that intelligent robots, in particular AI-based intelligent robots, will be an interesting research trend in ECE.

We summarize the specific research trends of intelligent robots in ECE that also respond to the discussion and research challenges.

- Integrating state-of-the-art AI technologies into intelligent robots for ECE, such as the AI-powered language model ChatGPT, to generate human-like interactive education with children.
- Investigating novel applications of AI-based intelligent robots to assist ECE, particularly the education of children with interaction disorders.
- Developing more AI educational tools with intelligent robots to show children visual AI concepts and applications, particularly interactive and practical AI educational systems.

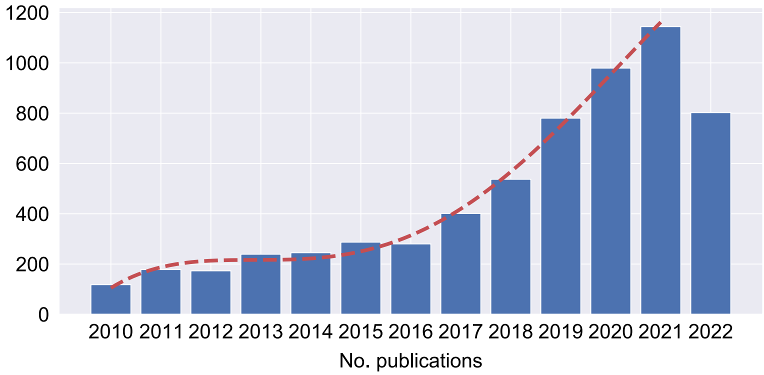

Fig. 9 The number of publications per year (from 2010 to 2022) on the topic of the key AI technologies in ECE. The red dashed line is the cubic polynomial fit of the number of publications. Scopus database returned 7134 results until 10/10/2022. (Color figure online)

5.2.2 AI technologies

In the past years, AI technology is significantly developed in many domains, e.g., ECE. We retrieve the literature on AI-based ECE with the keywords by the search code of title-abs-key((“artificial intelligence” OR “AI” OR “machine learning” OR “deep learning” OR “data mining” OR “virtual reality” OR “natural language processing”) AND (“early childhood education” OR “autism” OR “autism spectrum disorder” OR “ASD” OR “preschool” OR “kindergarten”)). The number of publications over the years is shown in Fig. 9. More and more studies apply AI technologies to ECE. The number of publications shows a growth trend from 2010. In particular, it shows a significant increase since 2017 which is a period of the explosive development of AI and its applications. In summary, various AI technologies are significant research trends in ECE.

We summarize the specific research trends of AI in ECE that are imminent and significant to be investigated.

- Developing useful and large-scale data and building various datasets for supporting AI applications in various ECE tasks due to the absence of good-quality data for AI in ECE.
- Developing real-time AI-based ECE models for childhood education on common computing systems.
- Applying state-of-the-art AI technologies to the ECE tasks for better ECE systems, such as interaction with ChatGPT.
- Extending novel applications of AI in ECE for improving early childhood education, e.g., using generative deep neural networks to generate ECE contents for AI-designed curriculum.

6 Conclusion

In this paper, we provide an up-to-date and in-depth overview of the studies of the key AI technologies in ECE by discussing the representative studies, delineating the historical perspective, and outlining open questions. We review the studies that apply AI-based robots and the key AI technologies to ECE, including improving the social interaction of children with an ASD. We discuss the challenges and trends through a detailed bibliometric analysis and provide insightful recommendations for future research. This paper significantly contributes to comprehensively reviewing the up-to-date studies, which are suitable as introductory material for beginners to AI technologies in ECE, as well as supplementary material for advanced users.

Although we present a complete overview of the existing literature on artificial intelligence in early childhood education, there are still multiple open issues and possible future work. Here, we outline some of them and highlight possible extensions of our work. First, we review the limited number of representative studies due to our limited knowledge and space limitations, some meaningful research findings may not be discussed in this paper. Second, this paper focuses on reviewing the studies of AI in ECE, social and economic factors were not discussed. We believe that the social and economic factors of AI in ECE are interesting for many readers. Finally, in the further, we will review the studies by cross-discussing our studies about AI in ECE for more technical details.

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Declarations

Confict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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