Stancin et al. *Research and Practice in Technology Enhanced Learning* (2026) 21:26
https://doi.org/10.58459/rptel.2026.21026

Research and Practice in
Technology Enhanced Learning

RESEARCH Free and Open Access

Trends in educational technology research: Examining seamless learning, metaverse and educational robotics

Kristian Stancin [1] *, Martina Holenko Dlab [1], Natasa Hoic-Bozic [1], Ivica Boticki [2] and Zoran Pribicevic [3]

*Correspondence:
kristian.stancin@inf.uniri.hr
Faculty of informatics and Digital Technologies,
University of Rijeka,
Radmile Matejcic 2, Rijeka,
51000, Croatia
Full list of author information is available at the end of the article

Abstract

Technology in education offers significant opportunities for innovation, particularly in the design of transformative and engaging learning activities. Prominent approaches in the field of technology-enhanced learning (TEL) include seamless learning, metaverse education and educational robotics, which together have potential to drive advances in education. This study employs bibliometric literature review to explore the potential of metaverse technologies and educational robotics in supporting seamless flow of learning across various contexts. Through keyword co-occurrence analysis, key themes, emerging trends and connections between these areas are identified. The findings highlight the central role of virtuality and artificial intelligence in enabling metaverse-based education and educational robotics. The research and development in digital twins, hybrid extended reality, immersive human-computer and human-robot interfaces, emerge as key topics in supporting seamless learning and personalized learning scenarios. This study highlights an underexplored area of aligning these technologies with pedagogical approaches, and identifies the need for the development of systems and data management approaches for seamless learning with the metaverse and robotics at a more general learner population level.

Keywords: Technology-enhanced learning, Seamless learning, Metaverse-based education, Educational robotics, Virtual reality, Artificial intelligence

Introduction

Technology-enhanced learning (TEL) integrates a variety of methods and systems to improve teaching and learning through technology. Within TEL, metaverse-based education has appeared as a transformative approach, utilizing immersive technologies to create interactive virtual environments (Gao et al., 2024). These environments support experiential learning, where students explore complex concepts, engage in simulations, and collaborate with virtual peers and teachers (Beck et al., 2024). Educational robotics enriches TEL by combining hands-on activities with virtual simulations, fostering problem-solving, creativity and STEM skills. Robotics enhances the impact of the metaverse by promoting engagement and collaboration through the integration of tangible and virtual tools (Benitti, 2012).

Seamless learning complements metaverse-based education and educational robotics by ensuring continuity of learning across formal, informal, and non-formal contexts. It bridges real and virtual environments, allowing learners to integrate and apply knowledge in different environments, thus enhancing the effectiveness of learning experiences (Wong, 2012).

This paper aims to contribute to the academic discussion in the field of TEL by performing a co-occurrence analysis to map the research landscape and identify key themes and trends in the literature for metaverse-based education and educational robotics. The paper especially explores the possibility of applying the principles of seamless learning for the integration of diverse environments and realities in which learning processes take place to overcome the challenges related to the use of metaverse technologies and robotics.

Related work

Despite the growing interest in seamless learning, the metaverse, and educational robotics, no prior studies that integrate these domains into a single review were identified. This lack of the combined research highlights a significant gap in the existing literature and serves as a motivation for this study.

Combined potential of seamless learning, metaverse-based learning, and educational robotics

To better understand the key concepts explored in this review, it is essential to define the domains of seamless learning, the metaverse, and educational robotics (Table 1).

To provide a clear conceptual framework for the intersection of seamless learning, metaverse, and educational robotics, it is essential to understand how these domains synergize through shared technologies and pedagogical goals. Seamless learning integrates real and virtual settings to create continuous educational experiences (Wong, 2012). The metaverse leverages VR/AR for interactive, experiential environments (Gao et al., 2024). Meanwhile, educational robotics merges hands-on activities with simulations to foster problem-solving, creativity, and STEM skills (Benitti, 2012). Figure 1 visually depicts these synergies.

Table 1 The description of seamless learning, the metaverse and educational robotics adopted for the purposes of this review

Domain	Description of the domain
Seamless learning	Seamless Learning (SL) is an educational approach that enables continuous integration of different learning environments, in formal, informal and non-formal contexts, using different devices and technologies. The main goal of SL is to create a personalized and fluid learning experience for students, allowing them to move seamlessly, imperceptibly and naturally between different educational contexts and technologies (Chan et al., 2006; Hambrock & De Villiers, 2023; Wong, 2012).
Metaverse	The metaverse represents a technology-enhanced environment that seamlessly blends virtual and real-world elements to create multi-sensory and interactive experiences. It utilizes advanced technologies such as VR, AR, blockchain, IoT and AI to create immersive spaces where users can interact with digital resources and other users, often represented by avatars. In education, the metaverse offers students the opportunity to learn outside the boundaries of the traditional classroom and experience contexts and scenarios that are not possible in the real world (De Felice et al., 2023; Gao et al., 2024; Zhang et al., 2022).
Educational robotics	Educational robotics integrates physical and virtual tools to create interactive, hands-on learning experiences across formal, informal, and non-formal contexts, using technologies such as programmable robots, simulation platforms and AI. It enables students to engage in problem solving and experimentation while providing opportunities for practical application of theoretical concepts (Benitti, 2012; Ospennikova et al., 2015; Tzagkaraki et al., 2021).

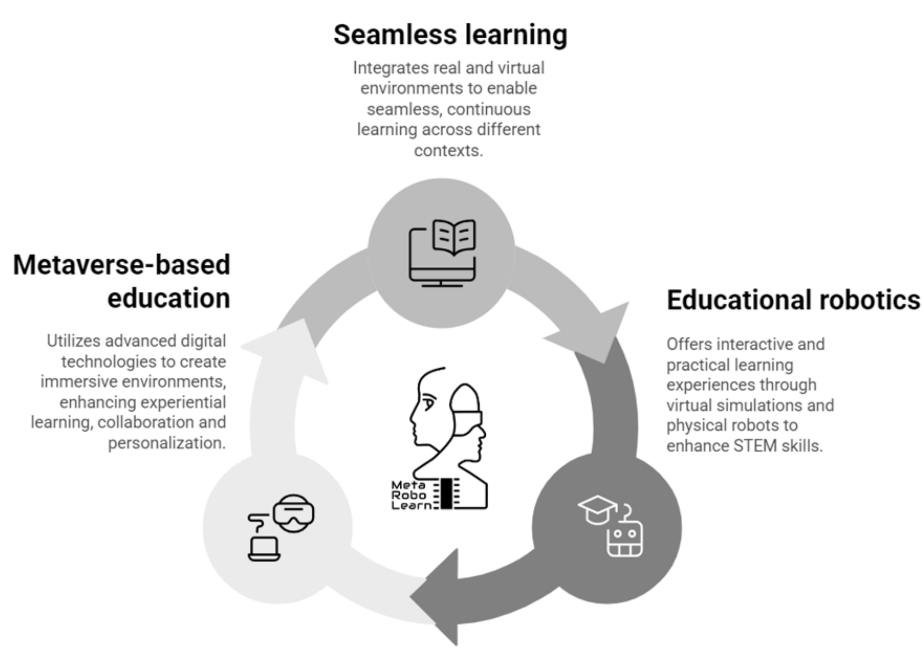

Fig. 1 Synergy of seamless learning, metaverse-based education and educational robotics

Together, these domains utilize advanced technologies like artificial intelligence (AI), digital twins who are real-time digital replicas of physical entities, integrating data from various sources (Pop et al., 2024), and hybrid extended reality (xR) which enables the integration of various immersive technologies to create personalized and engaging learning scenarios. In this context, xR and robotics enable personalized educational experiences through adaptive difficulty and multimodal feedback. A robotics-based conceptual model offers tailored learning resources aligned with each student's progress, ensuring challenges match their skill level. This approach supports a more effective learning process, improving engagement and outcomes (Ferjaoui & Cheniti Belcadhi, 2021).

At the intersection of seamless learning, the metaverse, and educational robotics, digital twins show promise to transform how students interact with immersive technology. Unlike static simulations, they maintain a two-way, real-time link between a physical robot and its virtual counterpart, mirroring sensors and student actions. This continuous synchronization lets learners shift fluidly between hands-on and virtual tasks, reinforcing cause-and-effect comprehension (Furini et al., 2022).

An illustrative use case involves primary-school students programming robots to navigate a pre-designed maze, replicated identically in both the classroom and a metaverse environment. They begin by coding the robot's digital twin with block-based tools, testing pathfinding and sensor inputs in a risk-free simulation. Every change is mirrored on the physical robot. Once students confirm success virtually, they confidently transition to hands-on tasks, seamlessly merging real-world exploration with interactive virtual learning.

Related literature reviews

To provide context and establish a foundation for this research, this section will review prior related review work in each of these areas.

Moon et al. (2024) reviewed 27 empirical articles (2014–2020) on learning analytics in seamless learning, highlighting the importance of observing students' behavioral dynamics across environments. Similarly, Talan (2021) analyzed 389 papers (1996–2020) in a co-word analysis, identifying key terms like seamless learning, mobile learning, ubiquitous learning, and mobile-assisted language learning as prominent themes.

Moresi et al. (2023) explored the conceptual structure of the metaverse, defining it as a convergence of virtual and physical worlds enabled by technologies like virtual and augmented reality, artificial intelligence, blockchain, and edge computing. Abbate et al. (2022) used bibliometric analysis to review metaverse studies, identifying core concepts such as presence, avatars, interoperability, privacy, and virtual goods. Al-kfairy et al. (2024) analyzed 35 empirical studies on metaverse adoption in education, finding that individual, technological, and environmental factors drive acceptance. Key topics included human-computer interaction, robotics, security systems, and education, with frequent keywords like virtual and augmented reality, second life, education and artificial intelligence. Regarding the field related to educational robotics, a study by Akgun and Atici (2023) aimed to determine the general trend of research in the field of educational robotics through a bibliometric analysis. The authors analyzed 1,382 papers (1975–2021) on educational robotics, identifying trends like computational thinking, STEM, coding, and social robots. Dou et al. (2024) conducted a visual exploration of educational robotics over five decades by visualizing top ten authors, organizations, countries, keywords, authors and sources. By analyzing 1437 articles, the authors identified the most important keywords by occurrence as educational robotics, robotics, education, computational thinking, STEM, children, programming and skills. Another study conducted a systematic review and bibliometric analysis of research on the use of robots in science education (Chiu et al., 2022). The findings identified three distinct clusters within the field: robots in elementary science education, robot-based STEM activities, and robot-facilitated computational thinking.

Real-world examples show how seamless learning, the metaverse, and educational robotics influence a range of contexts, including K-12 and corporate training. One project used agile methods with educational robotics in K-12, where students tackled problems in Scrum sprints via Scratch 3 (Konstantaras et al., 2024). Another integrated robotics to enhance emotional and social learning (Hamad et al., 2024). In higher education, NTUniverse replicated a campus for immersive collaboration (Sim et al., 2024), and developed a metaverse classroom advanced personalized, interactive VR/AR learning (Al Seiari et al., 2023).

Materials and methods

The methodology of this study is guided by the overarching research question: *How can the principles of seamless learning be applied to diverse learning environments and technologies, particularly in addressing challenges related to the use of metaverse technologies and robots in educational settings?* This question reflects the study's focus on exploring how metaverse technologies support seamless flow of learning across various contexts as well as their potential to promote a more personalized learning in the field of educational robotics.

Bibliometric analysis is employed to explore the structure of TEL literature, identifying conceptual relationships through keyword co-occurrence networks. This method models scientific knowledge as a complex system, visualizing connections among frequently occurring keywords to uncover core topics and emerging trends (Gutiérrez-Salcedo et al., 2018; Hota et al., 2020). Klarin's (2024) framework guides the systematic analysis, mapping significant themes and trends in educational research. This approach ensures comprehensive exploration of key developments, providing insights into both established and emerging topics.

Identification of a research domain and research question

Using a keyword co-occurrence analysis, this study aims to show how areas of seamless learning, metaverse and educational robotics overlap, identify emerging trends, and highlight their contributions to contemporary research in education. The review also aims to provide insights into the thematic connections within these fields, offering a high-level perspective on their collective potential to enhance teaching and learning processes.

The following specific research questions were defined:

RQ1) What is the conceptual structure of the literature on seamless learning and what are the key themes in education?

RQ2) What is the conceptual structure of the metaverse literature and what are the key themes in education?

RQ3) What is the conceptual structure of the robotics literature and what are the key themes in education?

RQ4) What are the trends, gaps and complementary topics in current research on seamless learning, metaverse and robotics in education?

These research questions provide a framework for analyzing the conceptual structure of the literature in TEL by mapping the key topics and visualizing clusters and connections. In addition, by revealing trends, gaps and complementary topics in these fields, this research also aims to identify emerging opportunities and areas that require further exploration for future research and practice.

Identification of the review scope

The next step of this research entails delineating its boundaries which is of great importance as this study aims to investigate the prevailing themes in seamless learning and educational robotics using metaverse. To ensure a comprehensive analysis of these areas and their overlapping topics, the inclusion criteria for sources are not restricted to peer-reviewed journal articles; grey literature, such as reports, theses, and working papers will also be incorporated.

The temporal scope of the study encompasses publications from the beginning of 2020 until the execution of the database query in October 2024, allowing for an examination of the most recent trends in the fields. Furthermore, the analysis is confined to the English language publications to maintain linguistic consistency. To enhance relevance and precision of the findings, papers lacking explicitly defined keywords are excluded from the dataset.

Search criteria and data extraction

This review utilized major scientific databases Scopus and Web of Science (WoS). Three distinct search queries were created for this purpose. The first query targeted papers that include the phrase seamless learning in conjunction with the terms *educ** or *teach**. The second query focused on papers combining the term metaverse with *learn**, *educ**, or *teach**. The third query identified papers referencing robot* in combination with *learn**, *educ**, or *teach**. To ensure that each query identifies research within an educational or teaching context, terms *educ** or *teach** were used. The term *metaverse* has been chosen over *virtual worlds* due to its broader and more comprehensive scope, which encompasses a wide range of immersive technologies and applications. While *virtual worlds* typically refer to computer-simulated environments where users can interact with each other and the digital surroundings, the *metaverse* extends this concept by integrating multiple cutting-edge technologies such as virtual reality (VR), augmented reality (AR), blockchain, and artificial intelligence (AI) to create a seamless and interconnected digital ecosystem (Zhang et al., 2022). All queries were configured to search for these terms within the title, abstract, and keywords of the publications. The database searches were conducted at the end of October 2024.

The first query yielded 73 results in Scopus and 41 in WoS, while the second produced 2439 (Scopus) and 1218 (WoS). Initially, the third query found over 55000 results in Scopus. After restricting to disciplines like computer science, engineering, mathematics, physics, social sciences, decision sciences, neurosciences, psychology, arts and humanities, and multidisciplinary studies, it narrowed to 49881 (Scopus) and 29133 (WoS). All citations were exported to CSV and organized into three distinct datasets.

Data set screening for inclusion

The paper aims to overview research trends and connections by analyzing and visualizing keywords. Data validation used both automated and manual reviews: duplicates were removed via a custom script, and papers missing keywords were manually excluded. This screening yielded final datasets of 72, 2136, and 42400 papers for the first, second, and third queries, respectively (Figure 2).

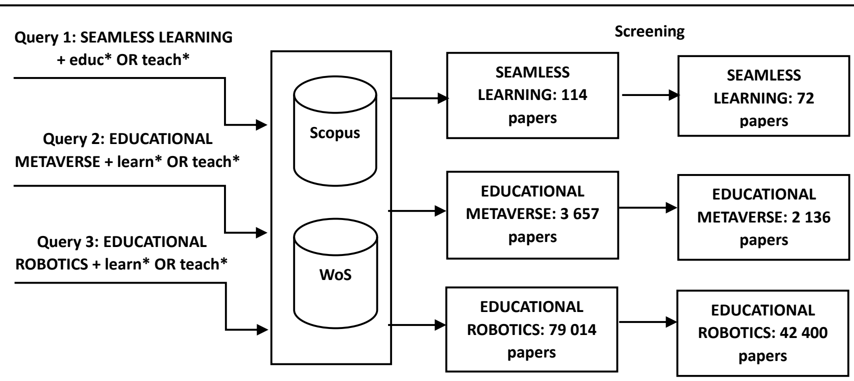

Fig. 2 The process of selecting papers

Mapping the results using informetric software

Following the retrieval of relevant papers, the data was imported into the VOSviewer tool, which facilitates the visualization of research clusters and themes, offering a comprehensive depiction of the research landscape (Klarin, 2024). To improve data discoverability and retrieval efficiency, a thesaurus file was developed to standardize keywords, integrate abbreviations with full terms, align synonyms, and unify singular and plural forms, thereby increasing the representation of keywords in search results (Porter, 2019; Slawsky, 2007).

Using the final datasets and the developed thesaurus, maps and clusters were created with the VOSviewer tool. During this process, it was necessary to define the minimum number of occurrences for a keyword. As this varies strongly according to the specific requirements and standards of a subject area (Sampagnaro, 2023), the thresholds were defined based on the characteristics of the datasets. For the first dataset, which deals with seamless learning, the minimum occurrence was set to 3. For the second dataset, which focuses on the metaverse, the threshold was set to 15. For the third dataset, which focuses on terms beginning with robot, the threshold was set to 100. These thresholds were chosen to ensure that the sufficient number of keywords meets the criteria while reflecting the scope and size of each dataset. They were also selected to avoid having too few nodes in the case of seamless learning and too many nodes in the other topics. This approach ensured a balanced and meaningful visualization of the keyword networks.

The mapping analysis and interpretation of results are given in detail in the following sections of the paper.

Results

This section presents the findings of a comprehensive bibliometric literature review that investigated the fields of seamless learning, the educational metaverse, and educational robotics. Key statistical indicators and visualized networks of co-occurring keyword clusters are analyzed for each of these domains. Additionally, the structural properties of the resulting keyword co-occurrence graphs are examined and discussed.

Table 2 provides an overview of the publication trends and types of research outputs across three fields. Educational robotics leads in total papers, followed by the metaverse and seamless learning. Publications in the metaverse and robotics rose steadily from 2020 to 2025, peaking in 2023, while seamless learning showed limited output. Journal articles dominate all fields, especially robotics and the metaverse, with conference papers also significant. Books, book chapters, and “other” types (reviews, surveys, letters) are rare across all fields.

Table 2 Number of papers per year and paper type

		Seamless learning	Educational metaverse	Educational robotics
Number of papers per year	2020	16	8	7355
	2021	15	14	8007
	2022	13	323	8299
	2023	22	939	9907
	2024	5	850	8720
	2025	1	2	112
	Total	**72**	**2136**	**42400**
Number of papers per paper type	Article	44	1062	21797
	Book/Book chapter	1	112	1037
	Conference paper	20	786	17998
	Other	7	176	1568

Table 3 summarizes the network properties of keyword co-occurrence graphs for the fields of seamless learning, the educational metaverse, and educational robotics. Educational robotics has the largest network, reflecting dense and cohesive research. The educational metaverse is smaller, with moderate interconnectivity. Seamless learning has the smallest network, indicating limited activity and weaker connections.

Table 4 highlights the top 10 most frequently used keywords in the fields of seamless learning, the educational metaverse, and educational robotics, ranked by total link strength, which indicates the degree of co-occurrence between keywords in each field.

Figure 3 shows the visualization of the co-occurrence network of keywords related to the field of seamless learning, with clusters indicating thematic connections.

Figure 4 highlights the co-occurrence network of keywords related to the metaverse, with distinct clusters representing interconnected themes.

The last visualization centers on robotics as the main keyword, highlighting its strong connections to fields like deep learning, artificial intelligence, and reinforcement learning. Additionally, since the area of educational robotics yielded the highest number of results, the graph was organized to displays links with a minimum strength of 50 for a better visual representation. This approach reduces the number of lines shown, enhancing readability. Details are shown in Figure 5.

Table 3 Graph properties

	Seamless learning	Educational metaverse	Educational robotics
Number of items on graph	13	55	152
Number of clusters	4	6	7
Total links	17	591	5112
Total link strength	31	4727	40867

Table 4 Top 10 most used keywords sorted by link strength

Field	Keywords	Occurrences	Total link strength
Seamless learning	Seamless learning	27	17
	Experiential learning	3	6
	Hybrid learning	4	6
	Lifelong learning	4	6
	Professional development	4	6
	Digital natives	3	4
	Learning	3	4
	Mobile learning	6	4
	Design-based research	3	3
	Learning analytics	3	2
Educational metaverse	Metaverse	1414	2199
	Virtual reality	510	1182
	Augmented reality	251	739
	Artificial intelligence	232	638
	Education	175	386
	Blockchain	142	384
	Machine learning	156	351
	Digital twin	123	311
	Extended reality	105	295
	Mixed reality	60	191
Educational robotics	Deep learning	5896	7299
	Robotics	4543	6791
	Machine learning	4370	6101
	Artificial intelligence	2582	4293
	Reinforcement learning	3401	3493
	Computer vision	1069	2109
	Convolutional neural network	1079	1510
	Internet of things	795	1408
	Object detection	854	1363
	Deep reinforcement learning	1387	1324

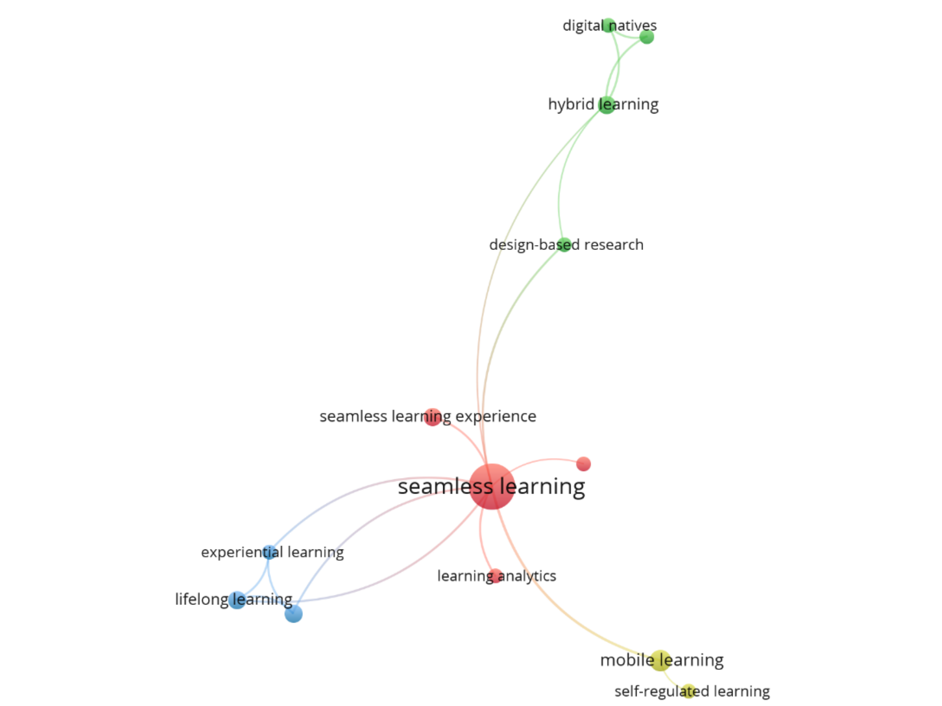

Fig. 3 Visualized networks of co-occurring keyword clusters for the field "Seamless Learning"

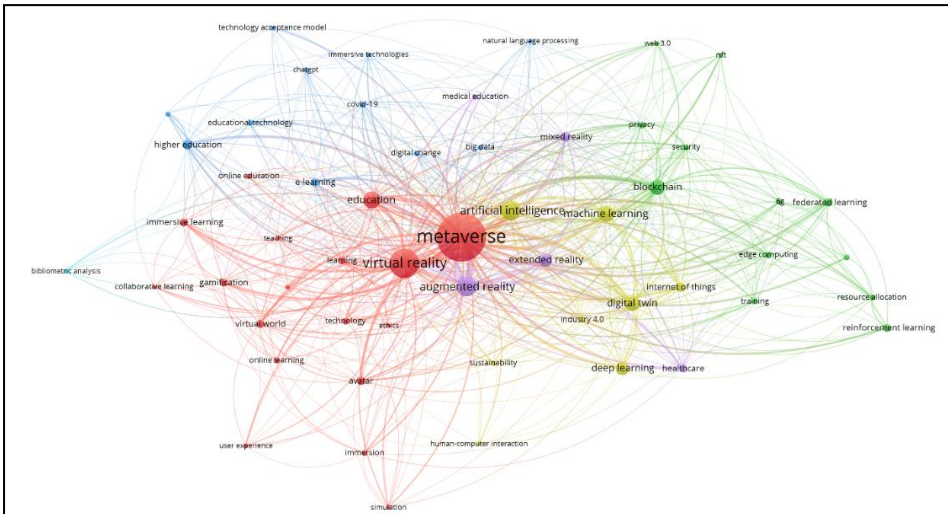

Fig. 4 Visualized networks of co-occurring keyword clusters for the field "Educational metaverse"

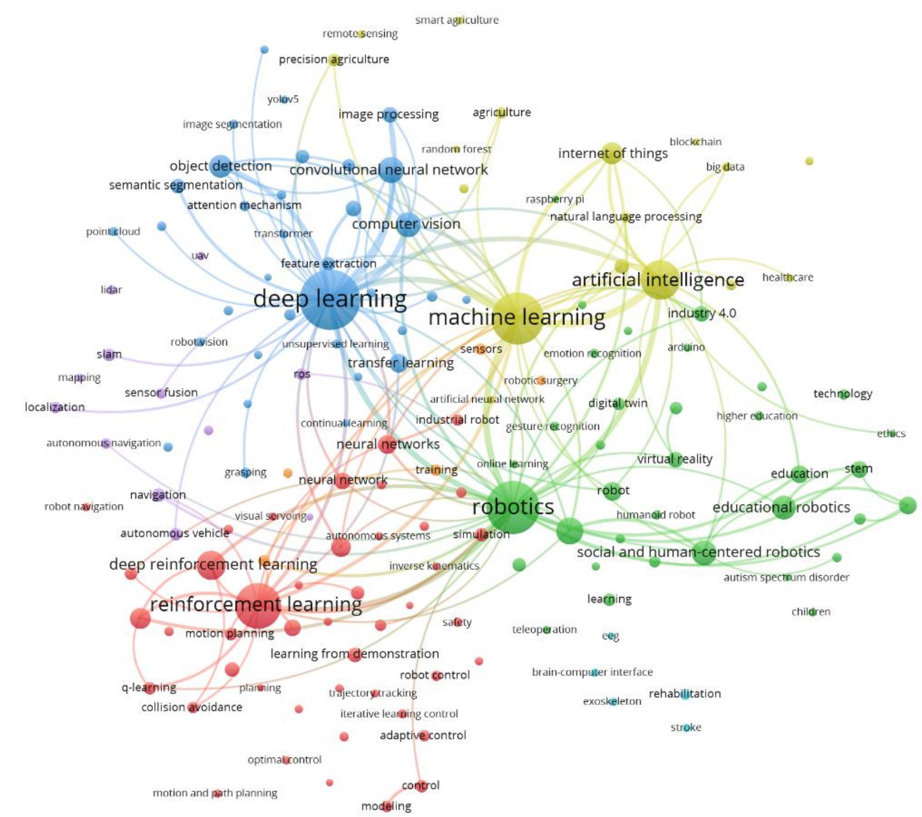

Fig. 5 Visualized networks of co-occurring keyword clusters for the field "Educational robotics"

All visualizations are elaborated upon in greater detail in the discussion section, where each area and its connections to other domains are thoroughly analyzed to provide a deeper understanding of their interrelationships and significance within the broader research context.

Discussion

Discussion related to the field of seamless learning

Compared to the other research areas analyzed as part of this study (metaverse and robotics), the area of seamless learning was found to be the least represented in the relevant literature throughout the last 5 years (Table 2).

The **first cluster** (red color) contains the keywords *seamless learning*, *higher education* and *learning analytics*. The keyword *seamless learning* is the central node and the co-occurrence with *higher education* shows that the use of seamless learning is more widespread at this level of education. The results of the study by Mykytiuk et al. (2022), in which the seamless learning model was evaluated with web-based tests, show that the presented seamless learning model can effectively improve *higher education*. Multiple learning activities have been shown to improve students' academic performance, motivation, approaches to learning and engagement. In Ayub et al. (2022) the application of seamless learning in *higher education* during the COVID-19 pandemic is described.

The presence of the keyword *seamless learning experience* shows that the papers describe various experiences of applied seamless learning, mostly from the field of higher education or adult education. For example, Chen et al. (2021) refer to adult education and show how blended learning can be designed and implemented to provide a seamless learning experience for learners in the workplace. Hambrock and De Villiers (2023) propose the Seamless Learning Experience Design (SLED) framework, which can be used as a guide for further research in the field of seamless learning in higher education.

It was also noted that one of the prominent topics in the literature on seamless learning is *learning analytics*. There are several studies on the trends and problems of learning analytics in seamless learning environments. For example, Moon et al. (2024) conducted an SLR on this topic and highlight the increasing integration of learning analytics to support inquiry-based and experiential learning, with a focus on formative assessment in digital contexts. They also suggested future research directions for learning analytics in seamless learning environments.

The **second cluster** (green color) comprises the keywords *Design Based Research* (DBR), *digital natives* and *hybrid learning*. Here, a slightly stronger co-occurrence is observed between the keywords *seamless learning* and *hybrid learning*, emphasizing the strong connection between these pedagogical models. In Ayub et al. (2022), a hybrid, seamless learning model of face-to-face and online learning was used, and a pilot study was conducted using the DBR methodology, which showed positive effects on learners. It is important to consider the characteristics of "*digital natives*" in a hybrid learning mode to enhance the seamless learning experience of learners (Napaporn et al., 2023).

The **third cluster** (blue color) includes the keywords *lifelong learning*, *professional development* and *experiential learning*, with a stronger co-occurrence between *seamless learning* and *lifelong learning*. According to Hımmetoglu et al. (2020), the most important qualifications of Education 4.0 are the integration of digital technologies in education, seamless learning environments, individualized education, explorative education and lifelong learning. Pornpongtechavanich and Wannapiroon (2021) describe research related to adult education, i.e., they explore the use of an interactive, intelligent learning platform for a seamless learning ecosystem to promote lifelong learning of citizens in the digital age.

The keyword *mobile learning* is a central node in the **fourth cluster** (yellow color) and its co-occurrence with seamless learning shows that the use of mobile technology is often linked to the design of a seamless learning environment. The impact of mobile seamless learning environments on student success and motivation is frequently studied (Poçan et al., 2023). This work was contextualized in secondary school settings and the results show that the use of mobile seamless learning was successful in motivating and improving student learning outcomes. Another example is the research on work-based seamless mobile learning (Casebourne, 2024).

In addition, the keyword *virtual reality* (VR) is presented as a separate cluster. Although there is no connection between the nodes seamless learning and VR in the graph, this technology is deemed important for seamless learning. Today, VR becomes more prevalent in educational settings and can help ensure a seamless learning experience (Liang et al., 2023; Malhotra & Fortino, 2024).

Discussion related to the field of metaverse

Research on the metaverse in education has grown exponentially in the last 5 years (Table 2) indicating that it has become a significant research field. Results of keyword co-occurrence analysis structures the literature on metaverse in six clusters, represented by keywords *metaverse*, *augmented reality*, *artificial intelligence*, *blockchain*, *higher education*, and *bibliometric analysis*.

The metaverse is a central node in the **first cluster** (red color). Its strong co-occurrence with education and virtual reality (VR) underscores their fundamental role in immersive *online learning environments*, as noted by Kye et al. (2021) and Park and Kim (2022), with students engaging in *virtual worlds* represented with *avatars* (Zhang et al., 2022). The connection with *user experience* highlights the need for effective design to improve interactions in *teaching* and *learning* within *virtual spaces*, as highlighted by Dwivedi et al. (2022). *Collaboration* and *gamification* emerge as key pedagogical strategies that enrich learning experiences, for example through problem-solving approaches combined with gamified challenges and rewards to boost engagement and motivation (Buhalis et al., 2023; Kye et al., 2021). The co-occurrence with **simulation** highlights the opportunities for experimental learning in risk-free environments (Lampropoulos et al., 2024). Finally, the co-occurrence of ethics points to growing concerns about privacy and the responsible use of emerging technologies in metaverse-based education (Dwivedi et al., 2022).

The **second cluster** (purple color) is represented by *augmented reality* (AR). Its strong co-occurrence with *metaverse, VR,* and *education* highlights the role of immersive technologies in advancing metaverse-based education. AR is often linked with VR, lifelogging, and mirror worlds as key components of the metaverse, accelerating its use as a "convergence service" (Kye et al., 2021). The strong co-occurrence of *AR* with *VR*, *extended reality (xR),* and *mixed reality (MR)* reflects a continuum of immersive environments under the umbrella term xR (Park & Kim, 2022). These technologies are frequently integrated to create hybrid approaches that enhance learning across disciplines. Notably, *medical education* emerges as a significant application, leveraging AR for interactive, visual learning and risk-free hands-on training (Dwivedi et al., 2022; Sharma & Jindal, 2024).

Artificial intelligence (AI) is one of the most prominent topics in the metaverse literature and represents the **third cluster** (yellow color). Combined with *machine learning* and *deep learning*, it can be used as a tool to analyze student activity, personalize learning, and support decision-making by identifying patterns and providing insights (Hwang & Chien, 2022; Simsek, 2024). Additionally, Dwivedi et al. (2022) emphasize the potential of *digital twins* that use AI to replicate the behavior and performance of students or other physical objects, systems or processes to create new and exciting learning opportunities that are dynamic and interactive. The role of human-computer interaction (HCI) is also crucial in making AI technologies intuitive and accessible (Said, 2023).

The blockchain and the associated **fourth cluster** (green color) highlight its role in creating secure, decentralized infrastructures for metaverse-based education. Challenges in governance and protocols in seamless virtual worlds stress the need to ensure *privacy* and *security* for educational records and interactions (Dwivedi et al., 2022). The co-occurrence of non-fungible tokens (NFTs) with metaverse and blockchain reflects interest in certifying and tracking performance, participation, and ownership of digital content in educational environments (Zhang et al., 2022). The connections of metaverse with VR, AR, and xR point to research into real-time, immersive interactions through advances in communications infrastructure (6G), decentralization (Web 3.0), providing smoother experiences (*edge computing*, *resource allocation*) and AI-driven interactions (*deep reinforcement learning*, *federated learning*) across metaverse platforms (Rafique & Qadir, 2024; Zhang et al., 2022).

The **fifth cluster** (dark blue color), represented by *higher education*, highlights efforts of higher education institutions to leverage new technologies for transforming teaching and learning. The co-occurrence of *immersive technologies*, *educational technology*, and *e-learning with metaverse*, *VR*, *AR*, and *xR* underscores their integration into higher education to create flexible, accessible, and engaging learning environments (Joshi et al., 2024). These technologies drive *digital change* and innovation, enabling interactive, student-centered approaches (Simsek, 2024). Applications include generative AI for content creation and AI assistants for student support (Al Yakin et al., 2024; Krauss et al., 2024). The presence of *natural language processing* (NLP) and big data highlights their role in improving education through learning analytics and informed decision-making (Hwang & Chien, 2022).

The last **sixth cluster** consists of only one keyword - *bibliometric analysis*. The co-occurrence of this keyword with others, primarily *metaverse*, *VR*, *AR*, *AI*, and *education*, suggests that this method is used to explore published research on the use of metaverse-based technologies for education, as in the following reviews conducted by Kulkarni et al. (2024) and Verma et al. (2024).

Discussion related to the field of educational robotics

The field of educational robotics presents the biggest and the most developed field analyzed as part of this study. With the 42400 papers in total and with a stable number of research papers throughout the five-year period covered by this study, the field of educational robotics has been rapidly developing to account for the rapid development of hardware and ever-rising availability of educational robotics kits and tools.

As shown in the presented analysis, the field is comprised of four major clusters: *the deep learning cluster*, *the robotics cluster*, *machine learning and artificial intelligence cluster*, and *the reinforcement learning cluster*. Such a composition of clusters illustrates the multidisciplinary nature of educational robotics as well as its strong dependence on cutting-edge and AI technologies.

The **first cluster** (blue color) represented the field of *deep learning*, which is essential for complex algorithms driving robots. This is supplemented by the co-occurrence of the keywords which deal with computer vision in general, such as the *robot vision*, *object detection*, *object recognition*, *machine vision*, *image processing*, *image segmentation* as the key task in deep learning (Minaee et al., 2021), along with the use of convolutional neural networks, which presents the de-facto underlying technology as the most utilized deep learning network type (Alzubaidi et al., 2021). Research efforts confirm that computer vision contributes to educational robotics learning outcomes enhancing the learning procedure (Sophokleous et al., 2021), while equipping robots with the ability of perceiving emotions and employing emphatic strategies significantly improves human-robot interaction performance (Brandizzi et al., 2021).

The **second cluster** (green color) encompasses the keywords related to the area of *robotics*, which is in this case an umbrella term for the less technical terms and presents an important cluster when examining educational robotics. The main identified co-occurrence of the term robotics with the terms *human-robot interaction* (Chen et al., 2024) and *social and human-centered robotics* reveals the contingent of studies which focus on the human-computer interaction approaches to educational robotics. In that context social robots are emphasized as innovations, harder for potential users to accept in human social compared to other innovations (Istenic et al., 2021). This is supplemented by a more specific co-occurrence of the keywords such as *gesture recognition*, *humanoid robots*, *child-robot interaction* and *emotion recognition*. A study examining gestures exhibited by the teachers identifies indicative gestures, one-hand beat gestures, two-hand beat gestures, frontal habitual gestures, and lateral habitual gestures, which educational robots should identify as part of the support to the educational processes (Gu et al., 2020). Important links are present when specifically examining the keyword educational robotics with co-occurs with the terms *STEM*, *computational thinking* (Yang et al., 2023) and programming (Tzagkaraki et al., 2021), with *higher education* and *engineering education* assuming a prominent position as educational fields. In terms of technologies, *virtual reality*, *augmented reality*, *digital twins, industry 4.0* and *Arduino* bring significant co-occurrence in the context of *human-oriented robotics*.

The importance of cutting-edge and AI technology is reflected in the **third cluster** (red color) which gathers keywords under the umbrella of *reinforcement learning*, indicating the importance of automatized decision making in robotics and educational robotics (Figueiredo Prudencio et al., 2024). The co-occurrence exists through the links with the terms *path planning*, *collision avoidance*, *trajectory planning*, *imitation learning*, *robot learning*, *obstacle avoidance* and other complex robotic learning approaches and algorithms that are necessary for achieving the complex behavior and logic of robots. The important co-occurrence links appear with the other clusters with the keywords *deep reinforcement learning*, *neural networks* and *discipline-specific robotics*, confirming that the reinforcement learning cluster presents the central element of the robotics use, including education (Lee et al., 2020).

The **fourth cluster** (yellow color) encompasses the keywords related to *machine learning* and *artificial intelligence*, such as the *internet of things*, *edge computing*, *big data* and *natural language processing*, which shows strong co-occurrence with the area of computing and data science in enabling robotic operation. Additionally, some co-occurrence is visible with the interdisciplinary fields of *agriculture* and *healthcare* which points towards the development of robotics in specific application fields with clear applied goals (Dang et al., 2023; Jiang et al., 2020).

The trends, gaps and complementary topics in seamless learning, metaverse, and educational robotics

The co-occurrence analysis shows that technology dominates the literature on metaverse-based education. Immersive technologies (VR, AR, MR) under the term xR are fundamental to experiential and simulation-based learning (Kye et al., 2021; Park & Kim, 2022). VR enhances online learning through collaborative and gamified approaches that improve engagement and problem-solving skills, while AR enables interactive, risk-free skill development that is ideal for fields like medical education (Dwivedi et al., 2022). Blockchain supports secure data management, credential verification and decentralized resource allocation, ensuring scalability and trust in TEL systems (Zhang et al., 2022).

The analysis also highlights the growing interest in technologies like AI, immersive tools and blockchain to personalize TEL. However, there is little evidence of practical implementation, pointing to a research gap. AI combined with learning analytics can adapt content to individual needs, enabling personalized, efficient learning (Simsek, 2024). Immersive technologies create adaptive, interactive environments (Hwang & Chien, 2022). For example, learners can control a physical robot through VR/AR, receiving multimodal feedback—audio prompts or visual overlays—to guide real-time improvements. Adaptive interventions offer immediate hints or step-by-step tutorials for struggling learners, while advanced learners unlock higher-level tasks (e.g., programming new behaviors). AI-driven analytics help instructors monitor progress and recommend resources in real time. Finally, micro-credentials supported by blockchain let students maintain transparent, transferable records of their skill development, reinforcing a personalized learning pathway that ensures appropriate challenges and motivation for all learners (Zhang et al., 2022).

AI techniques, including machine and deep learning, help analyze student activity, detect patterns, and tailor learning (Hwang & Chien, 2022; Simsek, 2024). NLP powers chatbots and intelligent tutors, while deep reinforcement learning refines adaptive robotics. Federated learning supports decentralized, privacy-preserving AI in metaverse-based education while maintaining data privacy (Rafique & Qadir, 2024). Digital twins facilitate seamless learning by creating real-time, synced virtual replicas of physical systems (Furini et al., 2022). Unlike static simulations, they exchange data continuously between digital and real environments. In a metaverse-based robotics lab, students can prototype control algorithms in VR or AR, then watch the physical robot mirror code updates in real time. This iterative feedback loop strengthens problem-solving, accuracy, and efficiency.

Although these advances are promising, socioeconomic barriers may hinder the scalability and accessibility of metaverse-based learning. The high cost of robotics kits, VR headsets, and computing resources restricts adoption, highlighting the need for affordable hardware solutions and reusable AR/VR applications (AlGerafi et al., 2023). In parallel, immersive interfaces and hyper-realistic avatars boost engagement but pose ethical challenges, including identity misuse if someone's likeness is used without consent. As these interfaces grow more prevalent, safeguards such as identity verification, watermarking, and consent-based avatar creation become crucial to ensure trust, security, and ethical practices (Dwivedi et al., 2022).

The analysis also reveals a research gap between the technological and pedagogical aspects of TEL. While terms like AI, xR and machine learning dominate, keywords such as collaboration, gamification and experiential learning appear less frequently, indicating limited focus on integrating these technologies into pedagogically grounded approaches. Future studies should explore the development of TEL systems that align technological advances with evidence-based educational theories to ensure immersive environments effectively support teaching and learning (Dwivedi et al., 2022; Gutiérrez-Salcedo et al., 2018; Hota et al., 2020). A valuable framework for aligning technology with pedagogy is TPACK (Mishra & Koehler, 2006), integrating technology, pedagogy, and content knowledge. By applying TPACK, researchers and practitioners can design innovative yet pedagogically grounded learning experiences. For instance, constructivism supports hands-on, learner-centered immersion, while connectivism stresses collaborative knowledge-building. Flipped classrooms, situated learning, and gamification balance theory and practice. Meanwhile, virtual labs and project-based tasks promote flexible access, deeper engagement, and skills development (Petraki & Herath, 2022). Bridging technological complexity and teacher readiness demands a multi-faceted strategy blending professional development, co-design, and phased implementation. Instead of purely technical training, programs must emphasize pedagogical integration and involve teachers as co-developers, ensuring alignment with classroom realities using design-based research approach. A gradual roll-out offers simpler applications first, building teacher confidence before expanding complexity (Dinçer, 2024; Limbong et al., 2024).

In hybrid xR contexts, inquiry-based and experiential learning thrive through immersive, interactive problem-solving experiences. However, over-reliance on automation poses risks: critical thinking and creativity are impaired, teacher guidance is neglected, and AI-driven decisions are biased (Mirzoeva et al., 2024). Hybrid xR technologies can accommodate neurodiverse learners (ASD, ADHD, dyslexia) and those with limited digital literacy by offering personalized, immersive experiences tailored to individual needs. They allow custom sensory inputs (brightness, sound, movement), adjust speed and content delivery, and simulate safe virtual social interactions (Damyanov, 2024; Ray & Zaveri, 2024). For limited digital literacy, they leverage spatial/visual cues, incremental game-based learning, and adaptive guidance, simplifying interactions (Morgan et al., 2016; Oyedokun, 2025).

Limitations

This study has several potential limitations that could affect the findings and interpretations. First, the bibliometric analysis is limited by the keywords chosen for inclusion, which could lead to selection bias (for example, the use of the term metaverse over the term virtual worlds). Publications not indexed or non-English may also be underrepresented, and researchers using alternate terms for the same concepts (especially “seamless learning”) could lead to the exclusion of relevant studies. A future systematic literature review with broader queries could better capture these variations, though it is beyond this paper’s scope.

Second, keyword co-occurrence may not fully reflect the varied pedagogical approaches used in TEL research, limiting understanding of how seamless learning, the metaverse, and educational robotics are practically applied. Moreover, because metaverse technologies are still evolving, fewer pedagogical frameworks might have emerged in current literature. A targeted review of pedagogical approaches, especially as experimental research with the metaverse grows, would offer deeper insights and enhance clarity on how these evolving technologies integrate into teaching and learning.

Conclusions

This study systematically analyzed and identified connections between seamless learning, the educational metaverse, and educational robotics, focusing on keyword co-occurrence to uncover emergent, correlating, and overlapping topics vital for technology-enhanced learning. Virtual reality (VR) plays an important role, enabling metaverse approaches and novel human–robot interfaces, such as lifelike humanoid robots with advanced gestures and emotional expressions. Similarly, seamless learning uses VR to fluidly switch between virtual and technological contexts, opening new pedagogical possibilities in metaverse and robotics education.

Looking ahead, digital twins, hybrid xR and simulation-based systems represent important research directions. Although AI encompasses many tools and approaches, it is an important foundation for educational robotics and metaverse design, with reinforcement and deep learning playing a key role. However, deploying these complex systems requires substantial setup, training and data management. Moreover, immersive technologies, like learning avatars, virtual assistants or generative AI, must take data protection, security and ethical considerations into account.

Ensuring equitable access remains a challenge, underscoring the need for cost-effective, scalable AR/VR solutions to broaden metaverse-based learning. AI-driven, immersive metaverse offer rich opportunities but also pose ethical risks such as deepfake misuse and identity theft, necessitating guidelines to protect users' likenesses. Generative AI in education should prioritize equity, transparency, accountability, and human oversight. Beyond UNESCO's AI ethics guidelines (UNESCO, 2021), frameworks such as IEEE's Ethically Aligned Design (Chatila & Havens, 2019), UNICEF's Policy Guidance on AI for Children (UNICEF, 2021), and EU AI guidelines (Tambiama, 2019) offer essential guidance.

Machine learning and deep learning serve as a base for learning analytics which is present in all three research areas as a major theme. It often relies on the data on learners and the surrounding technology use, which is collected across multiple dimensions of learning, in virtual or physical worlds, as AI-generated or human-generated and from a multitude of technology sources. Such a rich landscape of heterogeneous data requires specially designed data collection, processing, analysis and interpretation approaches. In seamless learning pedagogies, advanced data management enables personalization, collaboration, and gamification. Interoperable standards integrate learning systems across platforms, while AI-driven analytics embed reinforcement and adaptive learning algorithms. By dynamically adjusting content and scaffolding in real time, these approaches refine personalized instruction and strengthen inquiry-based, experiential learning.

Managing heterogeneous data in seamless learning requires robust data collection, processing, analysis, and interpretation. Multimodal data capture integrates sensor inputs, platform logs, and user interactions (e.g., eye-tracking), while Learning Record Stores using xAPI track learning across devices. Edge computing handles data locally on smartphones or IoT before cloud upload. Federated learning trains AI models on decentralized sources without moving raw data, protecting privacy. ETL (Extract, Transform, Load) pipelines standardize and cleanse data, and data lakes store unstructured formats (videos, logs). Finally, AI-driven adaptive models personalize learning paths, social network analysis measures collaboration, and predictive analytics suggests interventions, displayed via interactive dashboards.

Finally, the analysis highlights tools and technologies that have only recently emerged in mainstream education. Most studies focus on higher education or engineering education, where technology access and learner readiness are emphasized. Expanding the metaverse robotics dynamic to broader populations requires adaptable interfaces that bridge advanced tools to learning. Solutions combining metaverse and robotics for seamless, personalized experiences are still in development and need to be tailored to different contexts. By grounding these developments in pedagogical theories, the gap between technological innovation and effective educational practice can be bridged, making advanced technologies accessible and meaningful across learning contexts. The aim is to enable seamless transitions among metaverse technologies, providing uninterrupted learning via innovative robotics. Bridging technological and pedagogical gaps (e.g., with TPACK) will remove barriers to effective TEL.

Combining metaverse environments and robotics in education is promising yet underdeveloped. Advancing this requires interdisciplinary collaboration among educators, researchers, engineers, and legal experts to ensure pedagogical soundness, technical feasibility, and ethical responsibility. To assess long-term impacts, longitudinal studies should capture both quantitative and qualitative changes, including behavioral analytics (e.g., interaction patterns, response times) from metaverse/robotic systems and standardized skill assessments (e.g., Watson-Glaser Critical Thinking Appraisal, Teamwork Assessment Scales). Tracking engagement decay or skill plateaus could refine instructional strategies (Plano Clark et al., 2015; Sullivan et al., 2022; Vogelsmeier et al., 2024; Zhao et al., 2024).

This study lays the groundwork for integrating seamless learning, the metaverse, and educational robotics into a unified technological framework. The aim is to enable natural transitions among metaverse technologies, thus fostering immersive, robotics-assisted learning experiences. Bridging the technology-pedagogy gap remains crucial, prompting further exploration of pedagogical models to remove barriers.

Abbreviations

ADHD: Attention Deficit Hyperactivity Disorder; AI: Artificial Intelligence; AR: Augmented Reality; ASD: Autism Spectrum Disorder; DBR: Design Based Research; ETL: Extract, Transform, Load; HCI: Human-Computer Interaction; IoT: Internet of Things; MR: Mixed Reality; NLP: Natural Language Processing; SL: Seamless Learning; SLED: Seamless Learning Experience Design; STEM: Science, Technology, Engineering, Math; TEL: Technology-Enhanced Learning; TPACK: Technology, Pedagogy, and Content Knowledge framework; VR: Virtual Reality; WoS: Web of Science; xR: Extended Reality.

Acknowledgements

This paper is co-funded by National Recovery and Resilience Plan of the European Union, Project "MetaRoboLearn - Seamless learning with educational robots through the metaverse" (NPOO.C3.2.R3-I1.04.0194).

Authors' contributions

Kristian Stancin - Investigation, Methodology, Software, Data curation, Visualization, Writing - review & editing; **Martina Holenko Dlab** - Conceptualization, Investigation, Writing - review & editing, Writing - original draft, Resources, Supervision; **Natasa Hoic-Bozic** - Writing - original draft, Resources, Supervision, Writing - review & editing, Investigation; **Ivica Boticki** - Project administration, Writing - original draft, Funding acquisition, Investigation, Writing - review & editing, Supervision; **Zoran Pribicevic** - Resources, Investigation

Authors' information

K.S. is a postdoctoral researcher at the Faculty of Informatics and Digital Technologies, University of Rijeka.

M.H.D. is an associate professor at the Faculty of Informatics and Digital Technologies, University of Rijeka, head of the Chair of Multimedia Systems and e-learning.

N.H.B. is a full professor at the Faculty of Informatics and Digital Technologies, University of Rijeka and head of the Laboratory for the Application of Information Technologies in Education.

I.B. is a full professor at the Faculty of Electrical Engineering and Computing, University of Zagreb and head of the Department of Applied Computing.

Z.P. is the owner of the Microline company, which deals with domestic and foreign trade, production, repair and maintenance of electronic appliances and devices.

Funding

This paper is co-funded by National Recovery and Resilience Plan of the European Union, Project "MetaRoboLearn - Seamless learning with educational robots through the metaverse" (NPOO.C3.2.R3-I1.04.0194).

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author details

[1] Faculty of informatics and Digital Technologies, University of Rijeka, Radmile Matejcic 2, Rijeka, 51000, Croatia.

[2] Faculty of Electrical Engineering and Computing, University of Zagreb, Unska 3, Zagreb, 10000, Croatia.

[3] Microline d.o.o., Slavonska Avenija 26/9, Zagreb, 10114, Croatia.

Received: 30 January 2025 Accepted: 26 April 2025

Published online: 1 January 2026 (Online First: 2 September 2025)

References

Abbate, S., Centobelli, P., Cerchione, R., Oropallo, E., & Riccio, E. (2022). A first bibliometric literature review on Metaverse. In *2022 IEEE Technology and Engineering Management Conference: Societal Challenges: Technology,* *Transitions and Resilience Virtual Conference, TEMSCON EUROPE 2022* (pp. 254–260). IEEE. https://doi.org/10.1109/TEMSCONEUROPE54743.2022.9802015

Akgun, M., & Atici, B. (2023). Bibliometric map of educational robotics studies. *International Journal of Technology in Education*, *6*(2), 283–309. https://doi.org/10.46328/IJTE.402

Al Seiari, S., Al Kaabi, H., & Al-Karaki, J. N. (2023). Exploring immersive learning in the metaverse: A prototype for interactive virtual classroom. In *Proceedings of 2023 International Conference on Intelligent Metaverse Technologies & Applications* (pp. 1–8). IEEE. https://doi.org/10.1109/iMETA59369.2023.10294515

Al Yakin, A. M., Rasyid, A. R., Massyat, M., Muthmainnah, M., Aquino, A. B., Noche, T. H., & Cardoso, L. (2024). The importance of collaboration between human intelligence and GenAI in digitalization of education. In S. Mehta, S. K. Gupta, A. A. Aljohani & M. Khayyat (Eds.), *Advances in Computer and Electrical Engineering* (pp. 129–160). IGI Global. https://doi.org/10.4018/979-8-3693-5762-0.ch006

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023). Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education. *Electronics*, *12*(18), 3953. https://doi.org/10.3390/electronics12183953

Al-kfairy, M., Ahmed, S., & Khalil, A. (2024). Factors impacting users' willingness to adopt and utilize the metaverse in education: A systematic review. *Computers in Human Behavior Reports*, *15*, 100459. https://doi.org/10.1016/J.CHBR.2024.100459

Alzubaidi, L., Zhang, J., Humaidi, A. J., Al-Dujaili, A., Duan, Y., Al-Shamma, O., Santamaría, J., Fadhel, M. A., Al-Amidie, M., & Farhan, L. (2021). Review of deep learning: Concepts, CNN architectures, challenges, applications, future directions. *Journal of Big Data*, *8*(1), 53. https://doi.org/10.1186/s40537-021-00444-8

Ayub, E., Lim, C. L., Yeo, D. C. H., & Ismail, S. R. (2022). Developing a solution for hybrid classroom: A pilot study from a Malaysian private university. *Frontiers in Education*, *7*, 841363. https://doi.org/10.3389/feduc.2022.841363

Beck, D., Morgado, L., & O'Shea, P. (2024). Educational practices and strategies with immersive learning environments: Mapping of reviews for using the metaverse. *IEEE Transactions on Learning Technologies*, *17*, 319–341. https://doi.org/10.1109/TLT.2023.3243946

Benitti, F. B. V. (2012). Exploring the educational potential of robotics in schools: A systematic review. *Computers & Education*, *58*(3), 978–988. https://doi.org/10.1016/j.compedu.2011.10.006

Brandizzi, N., Bianco, V., Russo, S., & Wajda, A. (2021). Automatic RGB inference based on facial emotion recognition. *SYSTEM 2021*, 66–74.

Buhalis, D., Leung, D., & Lin, M. (2023). Metaverse as a disruptive technology revolutionising tourism management and marketing. *Tourism Management*, *97*, 104724. https://doi.org/10.1016/j.tourman.2023.104724

Casebourne, I. (2024). Left to their own devices: An exploration of context in seamless work-related mobile learning. *British Journal of Educational Technology*, *55*(4), 1772–1789. https://doi.org/10.1111/bjet.13410

Chan, T.-W., Roschelle, J., Hsi, S., Kinshuk, Sharples, M., Brown, T., Patton, C., Cherniavsky, J., Pea, R., & Norris, C. (2006). One-to-one technology-enhanced learning: An opportunity for global research collaboration. *Research and Practice in Technology Enhanced Learning*, *1*(1), 3–29. https://doi.org/10.1142/S1793206806000032

Chatila, R., & Havens, J. C. (2019). The IEEE global initiative on ethics of autonomous and intelligent systems. In M. I. Aldinhas Ferreira, J. Silva Sequeira, G. Singh Virk, M. O. Tokhi, & E. E. Kadar (Eds.), *Robotics and well-being* (Vol. 95, pp. 11–16). Springer International Publishing. https://doi.org/10.1007/978-3-030-12524-0_2

Chen, Y., Li, A., Wu, D., & Zhou, L. (2024). Toward general cross-modal signal reconstruction for robotic teleoperation. *IEEE Transactions on Multimedia*, *26*, 3541–3553. https://doi.org/10.1109/TMM.2023.3312944

Chen, Z., Chia, A., & Bi, X. (2021). Promoting innovative learning in training and adult education – A Singapore story. *Studies in Continuing Education*, *43*(2), 196–207. https://doi.org/10.1080/0158037X.2020.1772224

Chiu, M. C., Hwang, G. J., & Tu, Y. F. (2022). Roles, applications, and research designs of robots in science education: A systematic review and bibliometric analysis of journal publications from 1996 to 2020. *Interactive Learning Environments*, *32*(5), 1–26. https://doi.org/10.1080/10494820.2022.2129392

Damyanov, P. K. (2024). Effective pedagogical strategies and support mechanisms for enhancing the learning outcomes of students with special educational needs: A systematic approach. *International Journal of Scientific Research and Management*, *12*(10), Article 10. https://doi.org/10.18535/ijsrm/v12i10.el03

Dang, F., Chen, D., Lu, Y., & Li, Z. (2023). YOLOWeeds: A novel benchmark of YOLO object detectors for multi-class weed detection in cotton production systems. *Computers and Electronics in Agriculture*, *205*, 107655. https://doi.org/10.1016/j.compag.2023.107655

De Felice, F., Petrillo, A., Iovine, G., Salzano, C., & Baffo, I. (2023). How does the metaverse shape education? A systematic literature review. *Applied Sciences*, *13*(9), 5682. https://doi.org/10.3390/app13095682

Dinçer, S. (2024). Bridging the gap in technology integration in education: An examination of science teachers' competencies and needs. *Journal of Turkish Science Education*, *21*(4), Article 4. https://doi.org/10.36681/tused.2024.033

Dou, A., Xu, W., & Feng, Y. (2024). A visualized exploration of educational robotics over five decades. *International Journal of Technology and Human Interaction*, *20*(1), 1–21. https://doi.org/10.4018/IJTHI.356662

Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C. M. K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D. P., Gustafsson, A., Hinsch, C., Jebabli, I., … Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management*, *66*, 102542. https://doi.org/10.1016/j.ijinfomgt.2022.102542

Ferjaoui, D., & Cheniti Belcadhi, L. (2021). A conceptual model for personalized learning based on educational robots. In F. J. García-Peñalvo & A. García-Holgado (Eds.), *Proceedings of Eighth International Conference on Technological Ecosystems for Enhancing Multiculturality* (pp. 29–33). ACM. https://doi.org/10.1145/3434780.3436609

Figueiredo Prudencio, R., Maximo, M. R. O. A., & Colombini, E. L. (2024). A survey on offline reinforcement learning: taxonomy, review, and open problems. *IEEE Transactions on Neural Networks and Learning Systems*, *35*(8), 10237–10257. https://doi.org/10.1109/TNNLS.2023.3250269

Furini, M., Gaggi, O., Mirri, S., Montangero, M., Pelle, E., Poggi, F., & Prandi, C. (2022). Digital twins and artificial intelligence: As pillars of personalized learning models. *Communications of the ACM*, *65*(4), 98–104. https://doi.org/10.1145/3478281

Gao, H., Chong, A. Y. L., & Bao, H. (2024). Metaverse: Literature review, synthesis and future research agenda. *Journal of Computer Information Systems*, *64*(4), 533–553. https://doi.org/10.1080/08874417.2023.2233455

Gu, Y., Hu, J., Zhou, Y., & Lu, L. (2020). Online teaching gestures recognition model based on deep learning. In *Proceedings of 2020 International Conference on Networking and Network Applications* (pp. 410–416). IEEE. https://doi.org/10.1109/NaNA51271.2020.00076

Gutiérrez-Salcedo, M., Martínez, M. Á., Moral-Munoz, J. A., Herrera-Viedma, E., & Cobo, M. J. (2018). Some bibliometric procedures for analyzing and evaluating research fields. *Applied Intelligence*, *48*, 1275–1287. https://doi.org/10.1007/s10489-017-1105-y

Hamad, N. M. A., Adewusi, O. E., Unachukwu, C. C., Osawaru, B., Chisom, O. N., Hamad, N. M. A., Adewusi, O. E., Unachukwu, C. C., Osawaru, B., & Chisom, O. N. (2024). Bridging the gap: Using robotics to enhance emotional and social learning in K-12 education. *International Journal of Science and Research Archive*, *11*(1), Article 1. https://doi.org/10.30574/ijsra.2024.11.1.0025

Hambrock, H., & De Villiers, F. (2023). Proposing a Seamless Learning Experience Design (SLED) framework based on international perspectives of educators from five higher education institutions. *Electronic Journal of E-Learning*, *21*(1), 52–68. https://doi.org/10.34190/ejel.21.1.2497

Hımmetoglu, B., Aydug, D., & Bayrak, C. (2020). Education 4.0: Defining the teacher, the student, and the school manager aspects of the revolution. *Turkish Online Journal of Distance Education*, *21*(Special Issue-IODL), Article Special Issue-IODL, 12–28. https://doi.org/10.17718/tojde.770896

Hota, P. K., Subramanian, B., & Narayanamurthy, G. (2020). Mapping the intellectual structure of social entrepreneurship research: A citation/co-citation analysis. *Journal of Business Ethics*, *166*(1), 89–114. https://doi.org/10.1007/s10551-019-04129-4

Hwang, G.-J., & Chien, S.-Y. (2022). Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective. *Computers and Education: Artificial Intelligence*, *3*, 100082. https://doi.org/10.1016/j.caeai.2022.100082

Istenic, A., Bratko, I., & Rosanda, V. (2021). Are pre-service teachers disinclined to utilise embodied humanoid social robots in the classroom? *British Journal of Educational Technology*, *52*(6), 2340–2358. https://doi.org/10.1111/bjet.13144

Jiang, Y., Chen, C., Zhang, X., Chen, C., Zhou, Y., Ni, G., Muh, S., & Lemos, S. (2020). Shoulder muscle activation pattern recognition based on sEMG and machine learning algorithms. *Computer Methods and Programs in Biomedicine*, *197*, 105721. https://doi.org/10.1016/j.cmpb.2020.105721

Joshi, K., Kumar, R., Bharany, S., Saini, D. K. J. B., Kumar, R., Ibrahim, A. O., Abdelmaboud, A., Nagmeldin, W., & Medani, M. A. (2024). Exploring the connectivity between Education 4.0 and Classroom 4.0: Technologies, student perspectives, and engagement in the digital era. *IEEE Access*, *12*, 24179–24204. https://doi.org/10.1109/ACCESS.2024.3357786

Klarin, A. (2024). How to conduct a bibliometric content analysis: Guidelines and contributions of content co-occurrence or co-word literature reviews. *International Journal of Consumer Studies*, *48*(2), e13031. https://doi.org/10.1111/ijcs.13031

Konstantaras, A. J., Maravelakis, E., Giannakakis, G., Doitsidis, L., Spanoudakis, N., & Duca, E. (2024). K-12 agile learning with educational software and robotics technology. In *Proceedings of 2024 5th International Conference in Electronic Engineering, Information Technology & Education* (pp. 1–5). IEEE. https://doi.org/10.1109/EEITE61750.2024.10654428

Krauss, C., Bassbouss, L., Upravitelev, M., An, T.-S., Altun, D., Reray, L., Balitzki, E., El Tamimi, T., & Karagülle, M. (2024). Opportunities and challenges in developing educational AI-Assistants for the metaverse. In R. A. Sottilare & J. Schwarz (Eds.), *Adaptive Instructional Systems. HCII 2024. Lecture Notes in Computer Science, vol 14727* (pp. 219–238). Springer, Cham. https://doi.org/10.1007/978-3-031-60609-0_16

Kulkarni, P., Gaddi, A., Ramona, B., Popescu, V., Hiremath, V., K, S., Shetty, S. K., & Kagawade, S. (2024). A sustainable approach on metaverse in education: A SCOPUS-based bibliometric analysis to test TMIOS. In S. Idris (Ed.), *Global challenges for the environment and climate change* (pp. 189–211). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-2845-3.ch011

Kye, B., Han, N., Kim, E., Park, Y., & Jo, S. (2021). Educational applications of metaverse: Possibilities and limitations. *Journal of Educational Evaluation for Health Professions*, *18*. https://doi.org/10.3352/jeehp.2021.18.32

Lampropoulos, G., Fernández-Arias, P., Antón-Sancho, Á., & Vergara, D. (2024). Examining the role of augmented reality and virtual reality in safety training. *Electronics*, *13*(19), 3952. https://doi.org/10.3390/electronics13193952

Lee, C.-S., Wang, M.-H., Tsai, Y.-L., Chang, W.-S., Reformat, M., Acampora, G., & Kubota, N. (2020). FML-based reinforcement learning agent with fuzzy ontology for human-robot cooperative edutainment. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, *28*(06), 1023–1060. https://doi.org/10.1142/S0218488520500440

Liang, Y., Xiao, Y., Feng, G., Shell, J., Fahy, C., & Xing, Y. (2023). Towards a VR moot court for law students in enhancing practice experience. In *Proceedings of 2023 9th International Conference on Virtual Reality* (pp. 493–497). IEEE. https://doi.org/10.1109/ICVR57957.2023.10169153

Limbong, E., Setiawan, I., & Hamilton, A. (2024). Bridging the gap: The reality of digital technology integration by Indonesian pre-service EFL teachers. *Script Journal: Journal of Linguistics and English Teaching*, *9*(1), Article 1. https://doi.org/10.24903/sj.v9i1.1524

Malhotra, P., & Fortino, A. (2024). Teaching with Zoom vs. the metaverse a bandwidth use study. In *Proceedings of 2024 IEEE Integrated STEM Education Conference* (pp. 01–04). IEEE. https://doi.org/10.1109/ISEC61299.2024.10664999

Minaee, S., Boykov, Y. Y., Porikli, F., Plaza, A. J., Kehtarnavaz, N., & Terzopoulos, D. (2021). Image segmentation using deep learning: A survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *44*(7), 1–1. https://doi.org/10.1109/TPAMI.2021.3059968

Mirzoeva, A. M., Bostoganashvili, E. R., Vadov, A. A., Volkova, A. A., Gulov, A. P., & Platonova, N. I. (2024). Integrating hybrid learning into the higher education system: Challenges and opportunities. *Professional Discourse & Communication*, *6*(3), Article 3. https://doi.org/10.24833/2687-0126-2024-6-3-80-96

Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A framework for teacher knowledge. *Teachers College Record: The Voice of Scholarship in Education*, *108*(6), 1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x

Moon, J., Lee, D., Choi, G. W., Seo, J., Do, J., & Lim, T. (2024). Learning analytics in seamless learning environments: A systematic review. *Interactive Learning Environments*, *32*(7), 3208–3225. https://doi.org/10.1080/10494820.2023.2170422

Moresi, E. A. D., Pinho, I., & Costa, A. P. (2023). Metaverse: An analysis of the conceptual structure. In *Proceedings of 2023 18th Iberian Conference on Information Systems and Technologies* (pp. 1–7). IEEE. https://doi.org/10.23919/CISTI58278.2023.10211640

Morgan, R., Bryan, S., Meldrum, K., Mathiesen, B., & Hill, A. (2016). Using an adaptive e-learning curriculum to enhance digital literacy: Challenges and opportunities. In *Proceedings of the Australian Association for Research in Education Conference* (pp. 1–23). Australian Association for Research in Education.

Mykytiuk, S., Moroz, T., Mykytiuk, S., Moroz, M., & Dolgusheva, O. (2022). Seamless learning model with enhanced web-quizzing in the higher education setting. *International Journal of Interactive Mobile Technologies*, *16*(03), 4–19. https://doi.org/10.3991/ijim.v16i03.27257

Napaporn, S., Maneewan, S., Thamwipat, K., & Nittayathammakul, V. (2023). The Cloud-powered Hybrid Learning process to enhance digital natives' analytical reading skills. *International Journal of Advanced Computer Science and Applications*, *14*(1), Article 1. https://doi.org/10.14569/IJACSA.2023.0140168

Ospennikova, E., Ershov, M., & Iljin, I. (2015). Educational robotics as an inovative educational technology. *Procedia - Social and Behavioral Sciences*, *214*, 18–26. https://doi.org/10.1016/j.sbspro.2015.11.588

Oyedokun, T. T. (2025). Assistive technology and accessibility tools in enhancing adaptive education. In E. Çela, M. M. Fonkam, N. R. Vajjhala & P. Eappen (Eds.), *Advancing adaptive education: Technological innovations for disability support* (pp. 152–162). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-8227-1.ch006

Park, S.-M., & Kim, Y.-G. (2022). A metaverse: Taxonomy, components, applications, and open challenges. *IEEE Access*, *10*, 4209–4251. https://doi.org/10.1109/ACCESS.2021.3140175

Petraki, E., & Herath, D. (2022). Teaching and learning robotics: A pedagogical perspective. In D. Herath & D. St-Onge (Eds.), *Foundations of robotics: A multidisciplinary approach with Python and ROS* (pp. 43–62). Springer, Singapore. https://doi.org/10.1007/978-981-19-1983-1_2

Plano Clark, V. L., Anderson, N., Wertz, J. A., Zhou, Y., Schumacher, K., & Miaskowski, C. (2015). Conceptualizing longitudinal mixed methods designs: A methodological review of health sciences research. *Journal of Mixed Methods Research*, *9*(4), 297–319. https://doi.org/10.1177/1558689814543563

Poçan, S., Altay, B., & Yaşaroğlu, C. (2023). The effects of mobile technology on learning performance and motivation in mathematics education. *Education and Information Technologies*, *28*(1), 683–712. https://doi.org/10.1007/s10639-022-11166-6

Pop, E., Iliuţă, M.-E., & Moisescu, M. A. (2024). Digital twin types and applications in healthcare. In L. Stoicu-Tivadar, A. Benis, T. M. Deserno, S. D. Bolboacă, K. Saranto, M. Crişan-Vida, P. Gallos, O. S. Chirila, P. Weber, G. Mihalaş & O. Tamburis (Eds.), *Collaboration across disciplines for the health of people, animals and ecosystems* (pp. 32–36). IOS Press. https://doi.org/10.3233/SHTI241056

Pornpongtechavanich, P., & Wannapiroon, P. (2021). Intelligent interactive learning platform for seamless learning ecosystem to enhance digital citizenship's lifelong learning. *International Journal of Emerging Technologies in Learning*, *16*(14), Article 14. https://doi.org/10.3991/ijet.v16i14.22675

Porter, J. H. (2019). Evaluating a thesaurus for discovery of ecological data. *Ecological Informatics*, *51*, 151–156. https://doi.org/10.1016/j.ecoinf.2019.03.002

Rafique, W., & Qadir, J. (2024). Internet of everything meets the metaverse: Bridging physical and virtual worlds with blockchain. *Computer Science Review*, *54*, 100678. https://doi.org/10.1016/j.cosrev.2024.100678

Ray, P. R., & Zaveri, B. (2024). The role of technology in implementing effective education for children with learning difficulties. *The Scientific Temper*, *15*(04), Article 04. https://doi.org/10.58414/SCIENTIFICTEMPER.2024.15.4.53

Said, G. R. E. (2023). Metaverse-based learning opportunities and challenges: A phenomenological Metaverse Human–Computer Interaction study. *Electronics*, *12*(6), Article 6. https://doi.org/10.3390/electronics12061379

Sampagnaro, G. (2023). Keyword occurrences and journal specialization. *Scientometrics*, *128*(10), 5629–5645. https://doi.org/10.1007/S11192-023-04815-1

Sharma, N., & Jindal, N. (2024). Emerging artificial intelligence applications: Metaverse, IoT, cybersecurity, healthcare-an overview. *Multimedia Tools and Applications*, *83*(19), 57317–57345. https://doi.org/10.1007/s11042-023-17890-6

Sim, J. K., Xu, K. W., Jin, Y., Lee, Z. Y., Teo, Y. J., Mohan, P., Huang, L., Xie, Y., Li, S., Liang, N., Cao, Q., See, S., Winkler, I., & Cai, Y. (2024). Designing an Educational Metaverse: A case study of NTUniverse. *Applied Sciences*, *14*(6), 2559. https://doi.org/10.3390/app14062559

Simsek, A. (2024). How will education look like in the future? *Contemporary Educational Technology*, *16*(3), ep518. https://doi.org/10.30935/cedtech/14794

Slawsky, D. (2007). Building a keyword library for description of visual assets: Thesaurus basics. *Journal of Digital Asset Management*, *3*(3), 130–138. https://doi.org/10.1057/PALGRAVE.DAM.3650074

Sophokleous, A., Christodoulou, P., Doitsidis, L., & Chatzichristofis, S. A. (2021). Computer vision meets educational robotics. *Electronics*, *10*(6), 730. https://doi.org/10.3390/electronics10060730

Sullivan, E. V., Thompson, W. K., Brumback, T., Prouty, D., Tapert, S. F., Brown, S. A., De Bellis, M. D., Nooner, K. B., Baker, F. C., Colrain, I. M., Clark, D. B., Nagel, B. J., Pohl, K. M., & Pfefferbaum, A. (2022). Prior test experience confounds longitudinal tracking of adolescent cognitive and motor development. *BMC Medical Research Methodology*, *22*(1), 177. https://doi.org/10.1186/s12874-022-01606-9

Talan, T. (2021). Bibliometric analysis of the research on seamless learning. *International Journal of Technology in Education*, *4*(3), 428–442. https://doi.org/10.46328/IJTE.113

Tambiama, M. (2019). *EU guidelines on ethics in artificial intelligence: Context and implementation*. European Union.

Tzagkaraki, E., Papadakis, S., & Kalogiannakis, M. (2021). Exploring the use of educational robotics in primary school and its possible place in the curricula. In M. Malvezzi, D. Alimisis & M. Moro (Eds.), *Education in & with robotics to foster 21st-century skills* (Vol. 982, pp. 216–229). Springer International Publishing. https://doi.org/10.1007/978-3-030-77022-8_19

UNESCO. (2021). *Recommendation on the ethics of artificial intelligence*. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000380455

UNICEF. (2021). *Policy guidance on AI for children*. https://www.unicef.org/innocenti/reports/policy-guidance-ai-children

Verma, A., Patil, P., Paliwal, J. P. M., Bakhare, R., Pillai, R., & Singh, M. (2024). Conceptualising the importance of metaverse in education: A bibliometric analysis. *Journal of Ecohumanism*, *3*(6), 470–483. https://doi.org/10.62754/joe.v3i6.4018

Vogelsmeier, L. V. D. E., Jongerling, J., & Maassen, E. (2024). Assessing and accounting for measurement in intensive longitudinal studies: Current practices, considerations, and avenues for improvement. *Quality of Life Research*, *33*(8), 2107–2118. https://doi.org/10.1007/s11136-024-03678-0

Wong, L.-H. (2012). A learner-centric view of mobile seamless learning. *British Journal of Educational Technology*, *43*(1), E19–E23. https://doi.org/10.1111/j.1467-8535.2011.01245.x

Yang, W., Ng, D. T. K., & Su, J. (2023). The impact of story-inspired programming on preschool children's computational thinking: A multi-group experiment. *Thinking Skills and Creativity*, *47*, 101218. https://doi.org/10.1016/j.tsc.2022.101218

Zhang, X., Chen, Y., Hu, L., & Wang, Y. (2022). The metaverse in education: Definition, framework, features, potential applications, challenges, and future research topics. *Frontiers in Psychology*, *13*, 1016300. https://doi.org/10.3389/fpsyg.2022.1016300

Zhao, H. H., Shipp, A. J., Carter, K., Gonzalez-Mulé, E., & Xu, E. (2024). Time and change: A meta-analysis of temporal decisions in longitudinal studies. *Journal of Organizational Behavior*, *45*(4), 620–640. https://doi.org/10.1002/job.2771

Publisher's Note

The Asia-Pacific Society for Computers in Education (APSCE) remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.