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DEVELOPMENT ARTICLE

Is metaverse a buzzword in education? Insights from a systematic review

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Abstract

Although the metaverse is a trending topic in several fields, it is not a new concept within the field of education. In this study, we followed the PRISMA framework and identified 37 articles since 2008 that researched the metaverse in education. We critically reviewed these articles, aiming to examine the evolution of the field's conceptual understanding of the metaverse in education, identify its applications and effects, as well as synthesize the technical solutions and adoption challenges for implementing metaverse systems in schools. We found that the early empirical implementation of metaverse concepts in education mainly emphasized the characteristics of 3D virtual environments and avatars using the Second Life and OpenSim platforms. These traditional applications were found to be effective in supporting various teaching methods and enhancing students' learning experiences and outcomes. In recent studies, more advanced technologies that pursue the fusion of physical and virtual environments (e.g. AI techniques, VR/AR devices, cloud platforms, wearable devices) have been incorporated into metaverse systems. However, the extent to which physical and virtual environments were fused in metaverse applications in education needs to be further clarified. We suggest that the conceptual clarity of the metaverse in education will keep evolving along with the technology development, and teacher preparedness for this new technical revolution needs more attention.

Keywords Metaverse in education · Immersive learning environments · Emerging technologies

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Introduction

The rapid development of virtual environments supported by advanced digital technologies has put a spotlight on "metaverse", a term that was originally introduced in a science fiction novel in 1992 (Stephenson, 1992) and now has been widely used in various contexts projecting an outlook of the future virtual world. The evolution of this concept has taken around 30 years, along with the development of virtual reality (VR), augmented reality (AR) and cloud-based techniques. In recent years, the metaverse has received considerable attention from many sectors of our society. Researchers, game developers, and entrepreneurs envisioned the metaverse going beyond 3D virtual space to blend physical and digital environments, a concept of integration which spawns excitement and interest in applications in many domains, including education.

In the context of education, immersive and virtual learning environments can play a significant role in supporting online learning. There is an increasing interest in applying metaverse-related technologies in diverse educational settings to provide simulated learning environments and enhance teaching and learning effectiveness (Chen et al., 2022b; Lee & Hwang, 2022). However, it remains unclear how some previous studies implemented metaverse systems in education, and whether the "metaverse" in those studies is simply a buzzword that relabels the extended, augmented, and virtual reality technical solutions, or it possesses distinct characteristics that would lead to a transformation of online teaching and learning in the future.

Given that the metaverse has been studied in previous education literature, in this study we conducted a systematic review of the articles that explicitly addressed metaverse systems or examined the applications of metaverse systems in educational settings. It is critical to have a clear understanding of how the metaverse has been applied in education, and what experiences and lessons can be garnered. The focus of this study has three aims: (1) to critically analyze the conceptual understanding of the metaverse over time and identify the key characteristics of the metaverse in education; (2) to present research evidence on the applications and effects of the metaverse in education; (3) to identify the technical solutions for implementing metaverse systems in educational settings. Four research questions guided this study: (1) What is the metaverse in education?; (2) What are the applications of the metaverse in education?; (3) What are the effects of metaverse systems on students' learning?; and (4) What are the socio-technical solutions for implementing metaverse systems in education?.

Related studies

Since 2021, there have been several studies investigating the concept, components, enabling technologies, applications, and future agenda of the metaverse (Dwivedi et al., 2022; Lee et al., 2021). Lee et al. (2021) reviewed the metaverse as an ecosystem in which users reside and play in a permanent shared space and proposed six user-centered facets for metaverse development, including avatar, content production, digital economy, social acceptance, data protection, and credibility. The research agenda of metaverse development proposed in this study shows that there are still many problems to be solved prior to incorporating the metaverse in daily life. Other researchers defined the metaverse in a slightly different way, suggesting a holistic approach to building the metaverse as a massive alternative entity parallel to our physical world. Investigated the concepts and critical techniques of metaverse studies. They suggested the components of the metaverse include hardware, software, and content. When discussing education applications, the authors highlighted the potential of audio-visual-based applications in experiential education. In another study by Dwivedi et al. (2022), a set of expert views about the metaverse were consolidated, which highlighted that the metaverse could have a significant impact on education. These previous studies discussed the metaverse with a focus on its generic characteristics and applications without focusing on educational contexts.

Hwang and Chien (2022) conducted a narrative review of metaverse in education from an artificial intelligence (AI) perspective. They suggested that through the integration of AI, metaverse-based education systems could enable interactions among intelligent Non-player characters (NPCs), peers, and human learners. This fosters a continuous, immersive learning environment characterized by sustained, real-world-like scenarios where NPCs react based on user interactions for creating personalized experiences and memories. This dynamic and authentic environment contrasts with the scripted, short-term, and context-specific experiences in existing applications of VR or AR in education, underscoring the potential AI techniques in metaverse systems. Jagatheesaperumal et al. (2022) reviewed the technical challenges of educational metaverse applications. In contrast to the study by Hwang and Chien (2022), this study discussed the convergence of extended reality (XR) and internet of everything (IoE) as well as the critical features in the metaverse for educational training and skill improvement. Tlili et al. (2022) conducted a literature review on the metaverse in education using content analysis and bibliometric analysis. This study mainly focused on analyzing the bibliometric characteristics of studies on the metaverse in education and followed the conceptual framework of the Acceleration Studies Foundation (ASF) rather than analyzing the conceptual development of the metaverse based on the previous studies. Similarly, Kye et al. (2021) examined the educational use of metaverse concepts following the ASF framework and explained the potential usage of the metaverse in education. They also suggested that the misuse of student data should be addressed when implementing the metaverse for educational purposes.

Overall, current review studies of the metaverse in education mainly focused on the future potential of the metaverse without systematically examining the conceptual understanding of the metaverse in education based on previous literature. Other issues, such as the implementation of metaverse systems in education (e.g. teacher training, students' acceptance) and pedagogical implications were not examined in these review studies. In this study, we provide a systematic review to elucidate the research evidence on the conceptual understanding, applications and effects of the metaverse in education.

Methodology

Published literature related to metaverse in education was collected following the guidelines in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) (Page et al., 2020). The procedures for literature search and selection are summarized in Fig. 1. In total, 37 articles were included in the final dataset for the review analysis after a careful selection process. The detailed literature search process is described below.

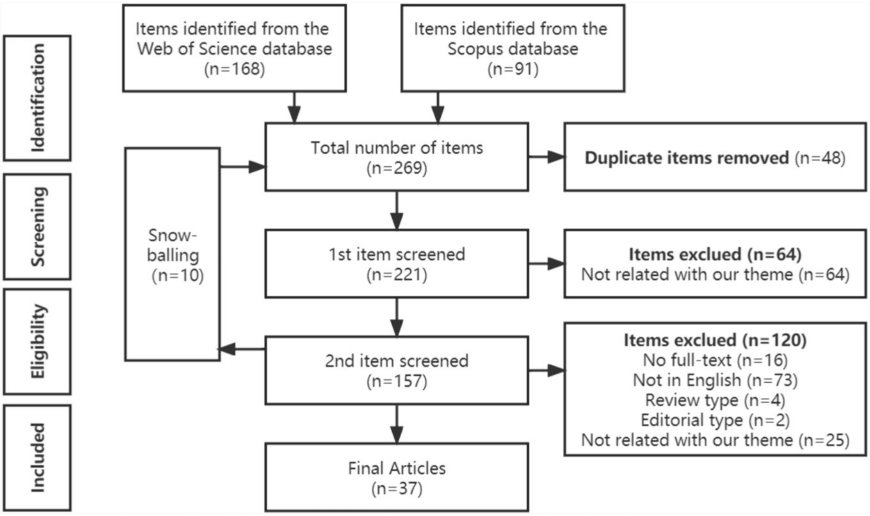

Fig. 1 Selection process

Search terms and search strategy

This study has a particular focus on metaverse applications in education. Two databases were used in this study, including Scopus and Web of Science (WoS). The respective search query was "TITLE-ABS-KEY(("metaverse") AND ("educa*" OR "learning"))" in Scopus, and "(TS = ("metaverse")) AND (TS = ("educa*") OR TS = ("learning"))" in the Web of Science. The search was conducted in April of 2022. All related publications based on the search query before April 2022 were retrieved from Scopus and WoS. A snowball sampling approach was further used to search the related articles from the reference lists of the preliminary search results. We found 168 relevant results from WoS and 91 publications from Scopus. After removing 48 duplicated articles as well as adding 10 articles from the snowball sampling, there were 221 articles for the further screening.

Eligibility criteria and selection process

We only included relevant empirical and conceptual articles published in English. Peer-reviewed journal articles (published/in-press), book chapters and conference papers were all considered. Two rounds of appraisal were conducted by two researchers and were carefully discussed within the research team to ensure the relevance of the articles in the final dataset. We excluded studies that did not investigate the metaverse in educational contexts, as well as the articles that only mentioned the term "metaverse" briefly in the background or discussion sections without providing any elaborations of the term. We only included articles that investigated metaverse as the key focus and had a clear educational context. The detailed inclusion and exclusion criteria are summarized in Table 1 below.

Table 1 Inclusion and Exclusion criteria

Inclusion criteria	Exclusion criteria
Language	
English	Other language
Literature type	
Journal article	Data paper
Book chapter	Erratum
Conference paper	Editorial article
Research type	
Empirical study	Review article
Conceptual article	
Relevance	
Studies should be related to metaverse in education/learning	Metaverse was studied in other contexts (e.g. business)
Both metaverse and education/learning should be clearly addressed	Only addressed one of the two aspects
The term, "metaverse" is treated as the key concept of the study	Metaverse was only mentioned briefly in the context or implication section with no further explanations

Analysis procedures

After the screening process, there were 37 articles in the final dataset for the analysis. These articles were analyzed according to four categories of information: 1) the operational definition of metaverse in these reviewed articles; 2) the educational problems or needs addressed and the corresponding metaverse-related techniques; 3) the effects of using metaverse techniques on students' learning; and 4) the implementation and adoption of metaverse systems in schools. Inductive analysis was used by applying open coding to the full texts of the reviewed articles based on the four categories. Two researchers were involved in the process to ensure the reliability of the coding results. The coding results were discussed within the research team multiple times to ensure consistency and reliability. The detailed coding results are presented in the Appendix A and Appendix B.

Results

Descriptive analysis of the reviewed articles

The earliest article in the dataset was published in 2008 (Collins, 2008) and only 17 studies were scattered from 2008 to 2015. After 2020, the number of studies on the metaverse surged significantly reaching 20 (Fig. 2). Overall, there were four types of articles in the reviewed dataset: Group 1—articles that conceptually discussed the definitions and applications of metaverse in education (6 articles); Group 2—articles that surveyed students' perceptions of metaverses without implementations (5 articles); Group 3—articles that introduced technical frameworks of metaverse systems in educational contexts (11 articles); Group 4—articles that empirically implemented metaverse systems in learning settings and collected empirical data to examine the effects of metaverse systems on students' learning (14 articles) and teacher training (1 article). The detailed coding results of the

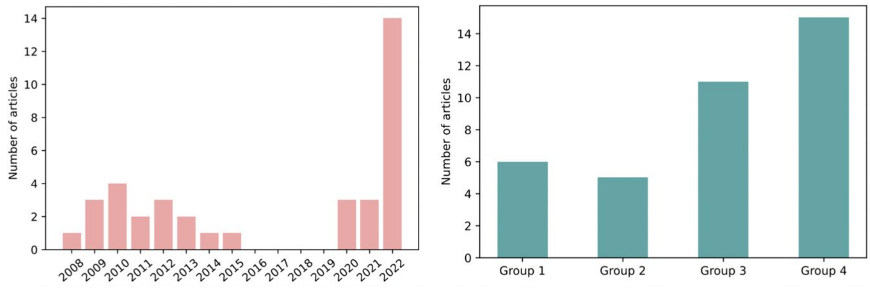

Fig. 2 Year and group distribution of the reviewed articles

reviewed articles for addressing all four questions are provided in Appendix A and Appendix B.

The reviewed studies involve both formal and informal learning environments with participants across various cohorts. Formal and informal learning can be differentiated based on whether learning activities take place in or outside school classes (Gerber et al., 2001; Hofferth & Sandberg, 2001). In this study, formal learning refers to the learning activities using metaverse systems in regular curriculum activities, and informal learning refers to the learning activities for students across age groups using metaverse systems that take place outside formal school setting such as after school programs and designed lab environments. Among the 37 studies, the majority of articles studied metaverse systems in formal educational settings in which students either used metaverse systems in classes or metaverse systems were integrated into the formal learning systems (N = 23) across higher education contexts (N = 14), elementary schools (N = 1), and high schools (N = 1). In addition, three studies focused on informal learning contexts where learners were involved in self-directed or non-traditional educational experiences (Itoh et al., 2009; Kanematsu et al., 2010; Tamai et al., 2011). The majority of the studies applied or discussed metaverse systems in higher education contexts (N = 22), and four studies involved participants from K-12 education. Regarding the regions of the participants in the reviewed studies, the majority of articles involved participants from various Asian countries (N = 23), including Japan, Korea, China, and Laos. Studies involving participants from North America, particularly the United States, also contributed significantly to this body of research (N = 6), in addition to the studies involving participants from other regions such as Europe, South America, and the Middle East.

Regarding the subject areas of metaverse applications in the reviewed studies (Group 3 & Group 4), the subject areas cover a wide range including both STEM subjects (N = 15), non-STEM subjects (N = 8) (see Appendix B). The involved STEM subjects include math, chemistry, agriculture, aircraft maintenance, biomedicine, electronics, engineering, medicine, radioactivity and nuclear safety (Alvaro-Farfan et al., 2020; Barry et al., 2015; Chen et al., 2022a; Chen et al., 2022b; Díaz et al., 2020; Itoh et al., 2009; Kanematsu et al., 2012, 2014; Khansulivong et al., 2022; Lee et al., 2022; Siyaev & Jo, 2021a; Siyaev & Jo, 2021b; Vernaza et al., 2012; Suzuki et al., 2020; Tarouco et al., 2013). The non-STEM subjects mainly focused on language education (Alvaro-Farfan et al., 2020; Guo & Gao, 2022; Kanematsu et al., 2010; Tamai et al., 2011; Torres-Arias & Trefftz, 2013) with two studies on music and archaeology (Getchell et al., 2010; Jaffurs, 2011). We noticed that there is an imbalance of metaverse applications towards non-traditional subjects in school curricula in the previous empirical studies, which tended to involve learning scenarios in higher education that require intensive hands-on experience and costly learning materials, such as medicine, aircraft maintenance and nuclear safety education. It also indicates a current research gap which is the lack of metaverse applications in traditional subjects such as maths, biology, and physics in K-12 education.

Conceptual understanding of metaverse in education (RQ1)

We analysed the conceptual understanding of metaverse in all four groups of articles in the reviewed dataset. The earliest article by Collins (2008) defined metaverse as the "convergence of virtually-enhanced physical reality and physically persistent virtual space". This conceptual understanding is well aligned with the concept of the metaverse proposed by Acceleration Studies Foundation (ASF) and other conceptual articles (Group 1) published in recent years that emphasize the fusion of physical and virtual reality (Akour et al., 2022; Almarzouqi et al., 2022; Chen et al., 2022a, 2022b; Mustafa, 2022; Park & Kim, 2022; Siyaev & Jo, 2021a, 2021b). In 2007, the metaverse roadmap published by ASF, a non-profit technology research institution, defined the metaverse as the fusion of a virtually augmented physical reality and a persistent virtual environment (Smart et al., 2007). The ASF has outlined two primary features for a metaverse with respect to the spectrum from augmentation to simulation. Augmentation refers to adding new features to users' physical world while simulation emphasizes introducing physically impossible functions or objects into virtual spaces (Park & Kim, 2022). Three types of metaverse were proposed by ASF in addition to the virtual worlds, including Mirror Worlds, Augmented Reality, and Lifelogging. Mirror Worlds focus on simulating real environments and physical properties, while Augmented Reality integrates digital information with users' environments. Lifelogging refers to the collection, processing, and distribution of daily information for people (Suh & Ahn, 2022). In general, the characteristics of metaverse defined by ASF are consistently discussed among the conceptual articles (Group 1) and technical articles (Group 3) in the reviewed dataset.

However, we found a gap between the conceptual understanding of metaverse in conceptual articles (Group 1) and the empirical implementations of metaverse in the reviewed articles (Group 4). The conceptual articles promote the fusion of virtual and physical worlds as one of the key characteristics of the metaverse, however, the early empirical studies mainly attributed the metaverse to 3D virtual environments and avatars developed through the Second Life and OpenSim platforms. The fusion of virtual and physical worlds has not been fully demonstrated and investigated in empirical studies. Among the empirical articles published between 2009 and 2015, Second Life and OpenSim are the major platforms used for implementing the metaverse (Barry et al., 2015; Kanematsu et al., 2010, 2012, 2014; Tamai et al., 2011; Tarouco et al., 2013; Yu et al., 2012). By analyzing these studies, we found that the early understanding of metaverse is heavily informed by these two platforms, with a strong emphasis on the characteristics of 3D virtual environments and avatars. These studies used Second Life or OpenSim to create 3D virtual environments simulating real-life learning settings or modelling learning objects to enhance students' learning experiences, and students were able to interact with each other and explore the virtual learning environments via avatars.

The 3D virtual environments offered by the metaverse provide an immersive learning experience. For instance, in one study held in a high school in the United States (Jaffurs, 2011), educators designed and built a SIMPhonic Island on the Second Life platform which included a virtual theatre, a class building, a garage and other scenes. Students were able to play an instrument in the virtual theatre and other avatars could stop by and listen. In another example in Japan (Kanematsu et al., 2014), the teacher used the Second Life platform to design a hands-on activity related to radioactivity and nuclear safety education in an elementary school. The virtual learning environment enabled students to engage in the learning activities that were not possible to conduct offline due to the safety and cost concerns.

In the 3D virtual environment, avatars are an important feature of the metaverse. Avatars refer to the digital agents created by individual users (Davis et al., 2009; Márquez Díaz et al., 2020; Yu et al., 2012). An avatar is regarded as a user's alter ego or representation of a user's presence in a virtual environment (Itoh et al., 2009; Márquez Díaz et al., 2020; Nakahira et al., 2010). Customizability is a significant feature of avatars. Users can customize their avatars by adjusting default clothing and face characteristics or create fully customized avatars using 3D modelling software (Jovanović & Milosavljević, 2022). Avatars also enrich the communication methods in the metaverse. By operating avatars, users can communicate with others via voice chat, body language, and facial expressions (Talan & Kalinkara, 2022). Students can also enact some behaviors which cannot be realized in the real world, for instance flying or transporting immediately to another scene (Marmaridis & Griffith, 2009). Students' eye blinking behaviors can also be synced with their avatars (Barry et al., 2015). Avatars can also enable students to develop a persona to represent their personality in a virtual environment (Getchell et al., 2010).

In addition, the metaverse was used to simulate real-world scenarios using both traditional platforms (e.g. Second Life and OpenSim) and immersive technologies (e.g. VR and AR) in the reviewed articles (Alvaro-Farfan et al., 2020; Torres-Arias & Trefftz, 2013; Barry et al., 2015; Getchell et al., 2010; Itoh et al., 2009; Jaffurs, 2011; Kanematsu et al., 2010, 2012, 2014; Khansulivong et al., 2022; Tamai et al., 2011). The resemblance with reality includes both modeling a real-world environment as well as replicating social interactions among users. The metaverse provides a computer-generated environment for online social interactions that imitates the real world while overcoming the physical restrictions (Torres-Arias & Trefftz, 2013). The immersive and gamification features allow the replication of real-life interactions and activities with the use of desktop applications and VR devices (Jovanović & Milosavljević, 2022). For example, in a study based on an aircraft maintenance class by Lee et al. (2022), the teacher used Unity 3D, a modelling engine, to create a simulated aircraft maintenance scenario that can support students to learn maintenance procedures, equipment, and terminology. Experts and beginners wearing VR devices could enter the metaverse environment together to learn aircraft maintenance knowledge and processes. The multi-user feature in the metaverse can provide students with an expressive and natural social learning setting, and support their communication and collaborations (Lee et al., 2022; Suzuki et al., 2020).

Beyond simulating realities, the metaverse supports students to create objects based on their perceptions and imagination (Márquez Díaz et al., 2020). This allows students to create fictional scenarios where physical laws may change or not exist, or can act as another extension of the real world. By operating avatars students can walk, run, and even fly and teleport to different locations (Davis et al., 2009), communicate with others in different locations (Kanematsu et al., 2010), and interact with objects without the risk of being injured (Jovanović & Milosavljević, 2022).

In addition to 3D virtual environments and avatars, the fusion of physical and virtual environments is a key feature of the metaverse (Akour et al., 2022; Almarzouqi et al., 2022; Chen et al., 2022a, 2022b; Mustafa, 2022; Park & Kim, 2022; Siyaev & Jo, 2021a, 2021b). However, this fusion cannot be achieved by using traditional platforms such as Second

Life and OpenSim. Most recent studies have leveraged cutting edge technologies such as mixed reality (MR) and artificial intelligence (AI) to support high-quality immersive experiences in virtual environments embedded in the physical world. For instance, in the study by Siyaev and Jo (2021b), mixed reality supported by Microsoft HoloLens2 smart glasses together with a speech interaction module was used to provide aircraft maintenance training. This provided students a virtual experience within the physical world and maximized the delivery of industry-level experiences. Some recent conceptual studies envision the future of the metaverse should include persistent and interconnected immersive platforms in which people can experience embodied communication and dynamic interactions with virtual objects in real time (Mustafa, 2022). The metaverse could evolve into a real virtual society in which gender, race and even physical disability will be dismantled with the development of multimedia technologies and blockchain technology (Duan et al., 2021).

Based on the reviewed studies, we summarized the common characteristics of metaverse as including: 3D virtual environment, avatars, resembling and simulating realities, and the fusion of physical and virtual environments. The last characteristic—fusion of physical and virtual environments—makes the metaverse a convergence of both virtually-enhanced physical reality and physically persistent virtual space (Collins, 2008). This plays a critical role in providing high quality immersive environments and determining students' learning experience in metaverse applications. The fusion of physical and virtual environments goes beyond AR/VR usage, requiring a broad range of advanced techniques such as holographic reality (HR) and spatial computing (Lee et al., 2023; Valaskova et al., 2022) to support the seamless blending of physical and virtual learning environments. However, in the current reviewed empirical studies, most studies mainly focused on using existing platforms and available AR/VR tools to resemble and simulate realities with avatars in a 3D virtual environments (e.g. Alvaro-Farfan et al., 2020; Torres-Arias & Trefftz, 2013; Jaffurs, 2011; Khansulivong et al., 2022; Tamai et al., 2011). The extent to which physical and virtual environments need to be fused in metaverse applications in education needs to be further clarified and informed by the continuous technology development.

Applications of metaverse in education (RQ2)

In the reviewed articles, the metaverse has been applied for supporting four types of teaching methods: (1) situated learning; (2) collaborative learning; (3) problem-based learning; and (4) game-based learning. The metaverse was found to be effective in providing an immersive, interactive, and engaging virtual environment to support teaching and learning in various areas, including medicine and engineering (Almarzouqi et al., 2022; Itoh et al., 2009; Lee et al., 2022), archaeology (Getchell et al., 2010), and culture and language learning (Tamai et al., 2011). In particular, medical and STEM education, which require hands-on experience, were the most frequently discussed subjects based on the number of articles in the reviewed dataset (Chen et al., 2022a, 2022b; Chen et al., 2022a, 2022b; Itoh et al., 2009; Jovanović & Milosavljević, 2022; Kanematsu et al., 2012; Lee et al., 2022; Siyaev & Jo, 2021a, 2021b; Suzuki et al., 2020; Vernaza et al., 2012; Yu et al., 2012).

The idea of situated learning stresses embodied engagement with the outside world and objects during the learning process (Anderson et al., 1996), which can be empowered by the simulation features of the metaverse. For example, in a class on Japanese culture and language learning, Tamai et al. (2011) developed a virtual learning space with Japanese style architectures using the Second Life platform. With the avatars, students could share their understanding of Japanese customs while walking around in the simulated environment. In another study by Chen et al., (2022a, 2022b), a virtual operating theatre was built according to a real clinical setting to help students get familiar with clinical scenarios. In an archaeology class, Getchell et al. (2010) reconstructed an excavation of a Byzantine Basilica, which allowed students to engage with antiquities and intuitively exercise their archaeological skills. A virtual environment resembling reality provides an effective way to support the development of students' embodied cognition and be better prepared for applying acquired knowledge in similar real-world contexts.

Fernández-Gallego et al. (2010) suggested that metaverse systems can be used to support collaborative learning effectively with social features. Fernández-Gallego et al. (2010) explained that the metaverse could enrich the continuous interactions among students through the design of 3D virtual learning scenarios, in addition to the traditional synchronous and asynchronous communications such as chat, email, and forums. Tarouco et al., (2013) believed that metaverse could improve the sense of active participation by using immersive resources in collaborative learning activities. To teach calculus for engineering courses, they developed a virtual learning laboratory with interactive learning materials such as videos, presentations, and fixation exercises. In this laboratory, students were asked to form groups with animated avatars to solve the presented problems, and they found this new instructional resource useful in this calculus course. Siyaev and Jo (2021b) developed a collaborative learning environment using mixed reality to facilitate students' collaborative learning concerning aircraft maintenance, which enabled students to communicate with speech commands and simultaneously work in the virtual environment together.

The immersive and interactive learning environment provided by metaverse was also used to support problem-based learning (PBL). In a PBL class, students would initially discuss a problem proposed by teachers and conduct an experiment to explore the questions further followed by a presentation reporting their results (Barry et al., 2015). The metaverse enabled students to interact with each other and conduct experiments in simulated environments. For instance, in the study by Kanematsu et al. (2012), a nuclear safety course was conducted in a metaverse environment. After a teacher gave a short lecture and proposed the problem, students discussed the problem via exchanging text messages in the metaverse. Although the interactions were conducted through a relatively traditional method, the simulated learning environment supported students to acquire nuclear energy knowledge, engage in productive discussions and generate strong interests in nuclear energy safety. In another study by Barry et al. (2015), three Japanese college students were invited to join the project to discuss simple and difficult problems respectively. They developed an eye blinking system in the metaverse which could synchronize avatars' eye blinking behaviors with their represented students in real-time. The experiment showed that the frequency of eye blinking was positively correlated with problem difficulty. The learning data recorded in a metaverse environment can also be analyzed to support the analysis of students' responses and behavior in order to provide timely interventions and support for enhancing learning outcomes.

The last common teaching method found in the reviewed articles supported by metaverse is game-based learning. In the study by Getchell et al. (2010), researchers created a 3D virtual learning space where students worked in teams to explore an archaeological site and then later presented their findings in an exhibition from the first-person point of view. By inducing the excavation concept in a game design, the excavation process was segmented into coherent stages. Students could advance between levels only after completing the current level with their teams. As a result, the gamification effect and learning effectiveness were well balanced and the excavation process was normalized and regulated. Getchell et al. (2010) highlighted that, in contrast to games, the metaverse supports inhabitants to develop laws and guidelines governing their realm rather than have predetermined goals or regulations. This provides the flexibility for encouraging students' creativity and motivations to engage in the designed GBL activities. Park and Kim (2022) analyzed and classified GBL virtual worlds in metaverse-related designs and stressed that it is critical to build GBL applications in the metaverse based on the interests and perspectives of students rather than teachers.

In summary, the current applications of metaverse in education that support teaching methods can be classified into three categories: (1) simulating the real world to provide an immersive environment and situational scenarios (Getchell et al., 2010; Lee et al., 2022); (2) facilitating interactions among students through avatars to accomplish teamwork (Kanematsu et al., 2010; Nakahira et al., 2010); and (3) expanding functions with other learning systems or tools (Barry et al., 2015; Guo & Gao, 2022).

Effects of using metaverse in education (RQ3)

Most of the empirical studies (Group 4) assessed the effects of metaverse on students' learning through questionnaires, pre- and post-tests, control and experimental groups, and interviews. Metaverse systems were used to support various STEM subjects (e.g. biomedicine, aircraft maintenance) and non-STEM subjects (e.g. English, archaeology). The effects of using the metaverse in education were found in four aspects: (1) enriching the learning experience, (2) increasing learning engagement, (3) enhancing learning outcomes, and (4) facilitating the development of social skills (Table 2).

Enriching learning experience

Metaverse systems can support students to practice theoretical knowledge in simulated learning environments in a self-paced and personalized way (Getchell et al., 2010). They can enrich students' learning experiences, particularly for subjects (e.g. medicine and STEM) with certain learning scenarios that are costly or infeasible to create in offline environments. For instance, in a lecture about eye structure and mechanisms (Itoh et al., 2009), an anatomical 3D eye model which was 400 times bigger than a real one was created on the Second Life platform. Students shown as avatars sat and moved together while listening to the explanations. Participants could have a close look at the magnified eyeball and could walk into the model to scrutinize the eye structure and learn its functions by watching the changes in details while explanations were presented both in voice and texts. This kind of virtual learning experience is not possible to be offered in offline settings. In another VR-based learning environment for aircraft maintenance (Lee et al., 2022), data on the participants' general presence, spatial presence, involvement and experienced realism were collected using the IGroup Presence Questionnaire (IPQ). The results showed that students' felt a sense of spatial presence, involvement, and experienced realism in the virtual learning environment.

Increasing learning engagement

Empirical evidence in the reviewed literature supports the effects of the metaverse in increasing students' cognitive, affective and behavioral engagement. Chen et al., (2022a, 2022b) found that the students who attended continuing medical education reported improvement in their perceived collaborative learning skills, communication skills and

Table 2 The effects of the metaverse in education

	Enrich learning experience	Increase learning engagement	Enhance learning outcomes	Facilitate the development of social skills
STEM				
Agriculture		Khansulivong et al., (2022)		
Aircraft maintenance	Lee et al., (2022)		Lee et al., (2022)	Lee et al., (2022)
Biomedicine	Itoh et al., (2009)	Itoh et al., (2009)	Itoh et al., (2009)	
Chemistry			Alvaro-Farfan et al., (2020)	
Math		Barry et al., (2015)	Alvaro-Farfan et al., (2020)	
Medicine		Chen et al., (2022a)		Chen et al., (2022a)
Radioactivity, nuclear safety		Kanematsu et al., (2012)	Kanematsu et al., (2012) Kanematsu et al., (2014)	
Non-STEM				
Archaeology	Getchell et al., (2010)	Getchell et al., (2010)		
English		Guo & Gao (2022) Torres-Arias and Trefftz (2013)	Alvaro-Farfan et al., (2020) Torres-Arias and Trefftz (2013)	
Japanese language and culture			Tamai et al., (2011)	
Multilingual discussion				Kanematsu et al., (2010)
Music		Jaffurs (2011)		

creativity after using the blended teaching model in metaverse, compared to the traditional online task-based learning. Students enjoyed navigating virtual learning scenarios and interacting with virtual objects (Díaz & Avila, 2020). Their motivations and curiosity were effectively stimulated (Tarouco et al., 2013). Guo and Gao (2022) analyzed students' electroencephalogram (EEG) data using deep learning models, and found that participants' cognitive engagement levels maintained at medium to high levels during the learning activities in the established experimental virtual environment for English learning. Students' learning interests and curiosity were also boosted by using metaverse applications (Getchell et al., 2010; Tarouco et al., 2013). Students reported they were interested in navigating and interacting with the virtual world (Díaz et al., 2020). For instance, in an online agriculture curriculum at a university in Laos, more than half of the participants have never used metaverse tools before, and more than 80% of students felt satisfied about the learning experience in the metaverse environment (Khansulivong et al., 2022). Similar results were found in the studies by Kanematsu et al. (2012) and Barry et al. (2015) where participants tended to enjoy the learning process. In the study by Itoh et al.(2009), all participants enjoyed the lecture in Second Life and 95% of them thought their understanding and interests were enhanced by using the 3D eyeball model. In addition, 29% of them had fun learning with others. In an online music course opened to American high students in Second Life (Jaffurs, 2011), students were intrigued about their 'flying' capability supported by the platform, and felt more secure and less stressed about their performance in the virtual world according to their interviews with the teacher.

It was also found that students had a high attendance rate and active participation in metaverse learning environments. In the study by Torres-Arias and Trefftz (2013), the attendance rate of university students in an English class on Second life was 0.8% higher than the classes in traditional classrooms. In another study by Getchell et al. (2010). Students had a high completion rate of the non-compulsory excavation work in an archaeology class. In another class about nuclear energy safety in Second Life, the participating college students performed actively with an emerging leader during the discussion, akin to in-person interactions in a classroom according to the teachers' observations (Kanematsu et al., 2012).

Enhancing learning outcomes

The empirical evidence from questionnaires and open answers (Itoh et al., 2009; Kanematsu et al., 2012, 2014), pre and post-test results (Alvaro-Farfan et al., 2020; Lee et al., 2022), comparable data analysis (Lee et al., 2022; Torres-Arias & Trefftz, 2013) and experiment log data of participants (Tamai et al., 2011), indicated that using the metaverse can help to enhance learning outcomes. In the study by Itoh et al. (2009), 95% of participants gained a deep understanding of eye structure by learning in the simulated virtual environment. In a Japanese culture class, students were shown to have a more concrete understanding of customs through operating their avatars in a situational architecture in Second Life, compared to learning from textbooks in classrooms (Tamai et al., 2011). Lee et al. (2022) conducted a pre- and post- test and found that participants who had no prerequisite knowledge of aircraft maintenance had a higher level of knowledge acquisition and better scores in the metaverse learning environment than the students who studied the same knowledge via traditional video training. The simulated learning environment also supported students to gain hands-on experience and master abstract knowledge. In the study by Kanematsu et al. (2014), six elementary students learned about radioactivity in Second Life and conducted hands-on tasks in a real classroom. All students understood this complex and abstract knowledge well according to their questionnaire and open-question answers.

Compared to teaching and learning in traditional classrooms, Alvaro-Farfan et al. (2020) found that student's academic performance in a metaverse environment (OpenSim) was higher than those in a traditional classroom in four subjects (i.e., math, chemistry, language, and literature) based on pre-and post-test results. In this study the difference in average scores of language and literature was not significant. Similarly, Torres-Arias and Trefftz (2013) experimented with teaching English as a second language to compare the learning effectiveness of two groups of university students in two different learning environments: a metaverse (Second Life) and a traditional classroom. Although the pre and post-test results showed that both methods (virtual and traditional) presented an improvement and a generally high level of learning effectiveness, the differences were not significant.

Facilitating the development of social skills

The metaverse can provide a multi-user interactive environment among avatars through real-time voice chats (Barry et al., 2015; Jaffurs, 2011) to facilitate students' interactions and collaboration. Three studies investigated the influence of the metaverse on students' social skills (Chen et al., 2022a; Kanematsu et al., 2010; Lee et al., 2022). In a metaverse class about aircraft maintenance (Lee et al., 2022), with the help of a cloud-based network, students were able to collaboratively maintain a virtual airplane together regardless of their geographic locations, through multi-party interactions. In another study about language, a language grid was used to support the social interactions among students from the US, Japan, and Korea (Kanematsu et al., 2010). Based on the survey results and analysis of the recorded conversations in this study, participants were found to be more active in discussions, and in particular a significant improvement was found for Japanese students who were more active in expressing their ideas in this virtual learning environment supported by a translation system. Similarly, participants in Chen et al., (2022a, 2022b) felt more confident in collaborative learning and communication skills.

Considering the effects of metaverse systems across subject areas, the four aspects introduced above were identified across STEM and non-STEM subjects in the reviewed empirical studies, with a majority of studies indicating the effects of metaverse systems on learning engagement and learning outcomes. Alvaro-Farfan et al (2020) was the only study that compared the effects of metaverse systems on students' learning achievements across disciplines including mathematics, language-literature, and chemistry, and claimed that students obtained higher academic achievement in mathematics and chemistry in metaverse based learning environments than in traditional classrooms. On the other hand, the difference in the academic achievement in language and literature was claimed not significant. The result of the study by Alvaro-Farfan et al (2020) was partially consistent with the study by Torres-Arias and Trefftz (2013), in which they found that although students achieved an average higher post-test score in both traditional and metaverse environments for English education, there was no significant difference in the score improvement between the two learning settings. However, based on these two empirical studies, we do not have sufficient evidence to provide a quantitative comparison of the effectiveness of metaverse systems across subjects. In addition, the reviewed studies adopted various approaches to examine the effects of metaverse systems in education, making a quantitative comparison across subjects and other conditions (e.g. formal and informal learning environments) challenging. This underscores the need for further exploration and research on comparing metaverse-based design and traditional teaching design within the same discipline and across disciplines, as well as investigating whether metaverse education holds particular advantages in STEM education, among other avenues for inquiry.

The socio-technical solutions for implementing the metaverse in education (RQ4)

Given the positive effects of the metaverse in education, it is critical to synthesize the technical solutions for implementing metaverse systems in previous studies. The early studies (2009–2016) mostly used Second Life or OpenSim platforms to create a metaverse learning environment. The implementation of metaverse systems indicated by previous studies includes: (1) selecting a software for creating 3D learning environments; (2) integrating the learning environments with existing learning management systems or resources; (3) using cloud platforms to support scalability and reliability; (4) deploying external databases to store data generated in learning processes; and (5) an analytical dashboard to support teachers' data-informed interventions and evaluations.

Technical solutions

For software implementation, a common first step was to choose a 3D platform (e.g. Second Life, OpenSim) to support and scaffold the creation of a 3D virtual learning environment and the accommodation of learning materials. However, most of the software options are not free. Schools need to pay for owning a virtual space, developing personal content, and maintenance (Rapanotti & Hall, 2010). As mentioned in the study by Nakahira et al. (2010), Nagaoka University of Technology built an isolated island in Second Life, where a series of educational experiments were conducted. However, it was inconvenient to build a large community on Second Life due to the costs. Compared to Second Life, OpenSim is an open source software that supports various programming languages with no costs. Using OpenSim, Tarouco et al. (2013) implemented a remote laboratory to teach engineering students calculus.

Different external platforms can be connected with Second Life or OpenSim to improve usability. Many studies concatenated the existing information systems in schools to a 3D virtual learning environment (Alvaro-Farfan et al., 2020; Getchell et al., 2010; Jovanović & Milosavljević, 2022; Márquez Díaz et al., 2020; Vernaza et al., 2012). For example, learning content management systems (LCMS) (e.g. Moodle) have been combined with OpenSim to manage learning materials and activities (Vernaza et al., 2012). With another metaverse-enabled learning system (Sloodle), any changes in content must be updated on both sides. In the study by Ariyadewa et al. (2010), assignments could be finished, submitted, graded in a metaverse environment, and added to students' profiles in Sloodle. In addition, **cloud platforms** (e.g. OSGrid) were often connected with metaverse systems to improve the scalability and reliability. Transferring the storage and processing into the cloud helps to resolve synchronization issues and access limits. Good receptors and stable internet connections are required for students to access the metaverse (Dahan et al., 2022). For example, in the study by Vernaza et al. (2012), by integrating the metaverse with the cloud-based OSGrid, students can access the virtual island using their computers, smartphones, or tablets from anywhere at any time.

External databases are essential to address the data storage issue and are thus a crucial component in metaverse implementation. Nakahira et al. (2010) deployed sensors in virtual school buildings to gather students' communication data. Accordingly, a database was linked to the metaverse environment in which the collected data could be stored long-term. In addition, there was an analytical dashboard to extract the data from the database and present the data in reformatted forms to provide teachers an intuitive way to grasp students' performance.

Extended reality (XR) technology has propelled recent studies into metaverse learning environments for students, centering on the integration of virtual reality (VR), augmented reality (AR), and mixed reality (MR) (Díaz et al., 2020). In recent years, the integration of extended reality (XR) technologies has gained significant traction in metaverse development. Educators now have the opportunity to leverage XR technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), to craft immersive learning environments. VR simulations, for example, enable hands-on learning experiences in fields like science and engineering (Lee et al., 2022), while AR overlays enrich real-world educational activities with digital content (Mustafa, 2022). The fusion represented by these approaches goes beyond the traditional web-based virtual learning platforms (e.g. Open Sim, Second Life), to integrate the Internet, web technologies, and extended reality (XR) (Dahan et al., 2022). In the study by Lee et al. (2022), researchers developed a VR-based metaverse system for aircraft maintenance. The implementation of this metaverse system included: (1) using the Unity3D game engine to create virtual objects; (2) deploying the virtual assets in head-mounted displays (HMDs); (3) integrating with AI modules (e.g. speech synthesis functions) to enable the interactions between the environment and users. In another study, Siyaev and Jo (2021b) created a similar collaborative virtual learning environment for aircraft maintenance to present an aircraft model to students. A Boeing 737 was simulated using Unity3D and augmented by a voice interaction module. The virtual 3D asset was embedded in Microsoft HoloLens, which allowed multiple students to collaboratively operate the aircraft model using both hand gestures and speech commands.

Blockchain technology is considered a key to effective data management and privacy protection in metaverse (Chen et al., 2022a, 2022b; Dahan et al., 2022; Duan et al., 2021; Jovanović & Milosavljević, 2022). In the metaverse architecture proposed by Jovanović and Milosavljević (2022), digital assets, currency, and user identity were stored in a blockchain network to prevent illegal content replication. In the blockchain-driven metaverse prototype proposed by Duan et al., (2021), an open source blockchain platform FISCO-BCOS was introduced to establish a blockchain-based ecosystem of the metaverse. They suggested that the non-fungible tokens (NFT) generated by blockchain could ensure the uniqueness and ownership of user-generated content, which would in turn, motivate the innovation of users and support the persistence of ecosystem operation in the metaverse. Blockchain integration offers robust data security and management capabilities (Chen et al., 2022a, 2022b; Chen et al., 2022a, 2022b). By harnessing blockchain technology, educational metaverse systems can ensure the authenticity and integrity of academic records, student achievements, and digital assets (Duan et al., 2021). Through blockchain-based authentication and encryption mechanisms, educators establish a secure framework for storing and verifying educational data while safeguarding student privacy. The integration of XR technologies and blockchain in educational metaverse systems heralds new opportunities for immersive and secure learning experiences that transcend traditional classroom boundaries.

Teacher adoption and student acceptance of metaverse systems

In addition to the technical solutions, the adoption of metaverse systems by students and teachers is also critical for the successful implementation of metaverse systems in schools. First, teachers are the key stakeholders in educational systems. Metaverse techniques should be strategically integrated into learning processes with a student-centered approach. The pedagogical suitability, teacher readiness, student affordance, and technical costs should be taken into consideration while implementing the metaverse in educational settings. The study of pre-service English teachers in Korea conducted by Lee and Hwang (2022) provided professional training on designing VR content as well as the relevant metaverse technologies. They found that through making VR content and hands-on practice, the participating teachers' technology competence and "Four Cs" (Critical Thinking, Creativity, Collaboration, Communication) were improved. The teachers' perceptions of the pedagogical benefits towards the VR usage in educational practices were also improved. Teachers play a critical role in accepting and creating effective virtual learning environments for enhancing students' learning. Therefore, teacher training and preparedness is an important condition for the success of metaverse implementations.

Second, students' acceptance of metaverse systems is an important factor for a successful implementation. According to a study by Suh and Ahn (2022), most Generation Z respondents reported prior experiences using metaverse related applications, such as Roblox or Pokémon Go, and indicated their interests in continuing using these applications (Suh & Ahn, 2022). Following the technology acceptance model (TAM), Akour et al. (2022) found that students' perceptions towards metaverse were affected by the personal innovativeness (PI), perceived ease of use (PEOU), and perceived usefulness (PU) of a metaverse system. In another study by Almarzouqi et al. (2022), researchers analyzed the intentions of 1858 university students for using the metaverse in educational settings. They found that PI was a significant indicator of metaverse adoption, and PI was independent from PEOU and PU. A higher level of PEOU and PU led to a higher level of intention to use. In addition, this study also showed that the students' perceived compatibility (PCO), perceived trialability (PTR) and perceived observability (POB) were significant predictors of adopting metaverse technologies. These findings highlighted the importance of the design of metaverse technologies for influencing students' acceptance.

Discussion

Through the systematic review of previous articles on metaverse in education, we synthesized the characteristics of metaverse in education, the key applications and effects, as well as the socio-technical solutions (Table 3).

Conceptual clarification of metaverse

Through this systematic review, we found that the conceptual understanding of metaverse evolves along with the progress of technology development. In the early stage (2008–2016), most studies used Second Life and OpenSim to develop metaverse environments for learning. Some studies associated metaverse with these platforms directly (Barry et al., 2015; Fernández-Gallego et al., 2010; Kanematsu et al., 2012, 2014; Tamai et al., 2011; Tarouco et al., 2013; Yu et al., 2012). Several studies expanded their current online learning management systems using Second Life to develop metaverse-enabled learning spaces (Fernández-Gallego et al., 2010; Marmaridis & Griffith, 2009). We found that the early understanding of metaverse was mainly informed by the use of Second Life and OpenSim, with a strong emphasis on 3D virtual environments and avatars.

Table 3 Summary of key findings

Characteristics of metaverse systems in education
● 3D virtual environment ● Resembling or augmenting reality ● Avatars ● Fusion of physical and virtual environments
Key applications of metaverse in education
● Support situated learning, collaborative learning, problem-based learning, and game-based learning by ● Simulating the real world to provide an immersive environment and situational scenarios ● Facilitating interactions among students through avatars to accomplish teamwork ● Expanding functions with other learning systems or tools
Key effects of metaverse in education
● Enriching learning experience ● Increasing learning engagement ● Enhancing learning outcomes ● Facilitating the development of social skills
Socio-technical solutions for implementing metaverse systems in schools
● Technical solutions: immersive technology, software systems, external platforms, cloud platforms, databases, analytical dashboards ● Adoption: teacher preparedness, students' perceptions

The recent development of wearable immersive technologies (e.g. smart glasses) have provided a higher quality of immersive environments, compared to the traditional computer-based platforms. WearablesIt can support multi-users to have real-time conversations and directly control the interactions with objects in virtual environments without holding a mobile device (Siyaev & Jo, 2021a). With 3D modeling and related hardware development (e.g. Unity 3D), the simulation of physical objects can also be produced in at a variety of sizes with all fine details supported by using smart glasses (Siyaev & Jo, 2021b). These technologies have enriched our understanding of metaverse, as users can have an embedded experience of the created virtual world with their physical movements and interactions, rather than control avatars to negotiate space in a 3D simulated environment. As a result, the fusion of the physical and virtual world is becoming feasible with the support of these technology advancements.

In this review, we found that there is a general consensus about the conceptual understanding of metaverse that embodies 3D virtual environment, avatars, and the fusion of physical and virtual worlds. The reviewed articles commonly referred the developed immersive learning environments as the metaverse (Alvaro-Farfan et al., 2020; Torres-Arias & Trefftz, 2013; Davis et al., 2009; Getchell et al., 2010; Itoh et al., 2009; Jaffurs, 2011; Jovanović & Milosavljević, 2022; Kanematsu et al., 2010; Marmaridis & Griffith, 2009; Nakahira et al., 2010; Suzuki et al., 2020; Vernaza et al., 2012). These immersive learning environments mainly leveraged available technologies to resemble or simulate 3D virtual environments in which students conduct various learning activities using avatars, and the level of immersion within the learning environments varied and highly depended on the utilized technical solutions. The extent to which physical and virtual environments are fused in metaverse applications within education needs to be further clarified, and we believe that the conceptual clarity of Metaverse will keep evolving and refined along with the technological development.

The socio-technical considerations for implementing metaverse

A primary goal of the metaverse in education is to leverage cutting-edge technologies to provide an effective virtual environment for enhancing students' learning. The implementation of metaverse systems in schools should take the complex socio-technical factors into consideration, including school structures, key stakeholders (e.g. teachers and students), learning processes, and technology affordance (Adams & Ivanov, 2015; Applegate et al., 2006). System-level support is also essential for the implementation of metaverse, including IT infrastructure readiness, funding support, as well as assessment and regulatory frameworks.

Teacher preparation

The articles reviewed in this study tapped on the teacher readiness and students' perceptions of the technology affordance of metaverse systems. According to Lee and Hwang (2022), teacher readiness is critical for ensuring the quality and sustainability of implementing metaverse systems in education. As the key agents in education systems, teachers play the role of renewed authority in metaverse-enhanced learning systems and environments. In addition to knowing how to use the systems, it is more critical for teachers to learn how to generate new content and design courses in virtual environments. Training on VR content generation and integrating the content into metaverse are important aspects to prepare teachers (Lee & Hwang, 2022).

New pedagogical approaches by teachers are also required to apply metaverse systems effectively in different subjects in education. In this study, we found that metaverse systems have been applied to subjects such as medicine and engineering to support students' hands-on practice with equipment and experiments (Chen et al., 2022a, 2022b; Lee et al., 2022). Another major application of metaverse systems was to provide authentic learning environments to support students' language and culture learning (Guo & Gao, 2022; Tamai et al., 2011). The approach to designing learning activities and content in metaverse systems could be different from the teaching design in traditional settings and depend on the desired learning outcomes in different subjects. In addition, teachers also need to explore new pedagogical approaches considering how to integrate the learning activities in metaverse systems with the other learning activities that would take place in classrooms or online settings. This creates new challenges and opportunities for teachers to provide a balanced and holistic learning experience leveraging the resources and strengths of both physical and virtual learning environments to enhance students' learning.

Students' acceptance and involvement

The technical affordance for students should be well examined and considered to ensure that the usage of metaverse systems can enhance students' learning outcomes rather than introduce new cognitive burdens or hinder their learning effectiveness. The study by Akour et al (2022) indicated that students' attitudes toward metaverse-based learning is closely associated with their perceived difficulty and usefulness of the metaverse. Thus, student-oriented design of metaverse systems is key for successful applications. A study by Talan and Kalinkara (2022) showed that in general students have a positive attitude toward metaverse usage in education (Talan & Kalinkara, 2022). Potential benefits indicated by students include more interactions with classmates and teachers, an enjoyable learning environment and content, and convenience in time and distance. All these are significant factors that should be fully considered by teachers and system developers. Students' involvement in the design and implementation of metaverse systems by sharing their needs and expectations, as well as their perceptions towards the metaverse systems can lead to a successful implementation.

In addition, the implementation of metaverse systems should be well integrated into students' learning processes. The empirical evidence from the reviewed studies demonstrated that metaverse-enabled learning environments can be effective in increasing students' learning motivations, encouraging them to develop personalized learning methods, and acquiring efficient self-directed learning experiences (Akour et al., 2022). This also echoes the suggestion for teachers to develop novel teaching methods to support the integration of immersive technologies into learning processes.

System-level considerations

At the school level, leaders and policymakers should take a holistic approach to implementing metaverse systems in view of educational visions, funding situations, current IT infrastructure, and teachers' technology competence. Schools are suggested to have customized implementation plans based on the assessment of these aspects, and take steps to implement and improve the metaverse applications in practice. Based on the analysis results of the technical solutions of metaverse systems in this review, several platforms used in the reviewed studies can be considered by schools for implementing metaverse applications. Second Life, Opensim, Roblox, and Frame VR are popular virtual world platforms that could be integrated into existing learning management systems. With the development of immersive technologies and the popularization of VR devices, VR/AR/MR-based metaverse learning scenarios have gradually matured and expanded. However, the schools should take the demand on funding and resources into consideration with respect to costs including acquiring devices, setting up the required infrastructure, and teacher training. The implementation scalability could be constrained by the available funding and resources. This constraint could be overcome as the technology for high-quality metaverse systems becomes increasingly affordable in the future. In summary, schools are recommended to have a systematic evaluation of the social and technical conditions and develop sustainable strategies for implementing, maintaining, and updating metaverse systems in the long run.

Future directions

Future studies should make continuous efforts to provide empirical examples on the fusion of virtual and physical space advocated in the current conceptual papers (Park & Kim, 2022). The effects of metaverse applications on students' socio-psychological development should also be investigated, beyond their learning outcomes and experiences. The multimodal data generated in metaverse learning environments can be a rich data source for learning analytics research. In addition, as metaverse provides a new learning environment, it calls for novel pedagogical methods for leveraging the metaverse to enhance students' development. For instance, more investigations are needed on how to design effective learning scenarios and personalized avatars to facilitate student learning in virtual settings, while taking the potential subject variance into consideration. Moreover, future studies are recommended to explore the applications of metaverse systems in traditional subjects in school curricula in K-12 settings, which is lacking in the extant literature. Future studies should also look into the potential subject difference on the effects of metaverse applications via conducting experimental studies within and across subjects.

The roles of students and parents in the design of metaverse systems are underrepresented in current studies. Future studies should study the involvement of students and parents in the design of the environment and further explore how the metaverse could be applied in family education. In addition, previous empirical studies tended to have small sample sizes (e.g. three participants), which could be due to the limited availability of devices. Large-scale experiments and longitudinal studies are needed to examine the effects of the metaverse on students' development. Lastly, ethical concerns should not be overlooked while using the metaverse in education, including data privacy and safety usage.

Conclusions

This article draws on empirical evidence from previous studies to understand the conceptual development, applications, and effects of the metaverse in education. Through this review, we found that there is still a gap between the empirical applications of 3D virtual environments and avatars and the conceptual understanding of metaverse with respect to the fusion of virtual and physical environments. Metaverse applications are effective in supporting a variety of teaching methods to enhance students' learning. However, pedagogical suitability, teacher readiness, student affordance, and technical costs should be taken into consideration while implementing the metaverse in educational settings.

Appendix A

Coding results of reviewed articles (part 1).

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
1	Chris Collins (2008)	United States (US)	North America	1	"The Metaverse is the convergence of 1) virtually-enhanced physical reality and 2) physically persistent virtual space. It is a fusion of both, while allowing users to experience it as either".	NA	NA
2	Davis et al., (2009)	US	North America	1	"Metaverses are immersive three-dimensional virtual worlds (VWs) in which people interact as avatars with each other and with software agents, using the metaphor of the real world but without its physical limitations".	NA	Virtual team collaboration
3	Itoh et al., (2009)	US & Japan	Cross-region	4	"The 'Metaverse' is not only a cyber-space with a space simulator, but also a virtual world with social activities. There, users can interact with other users through so-called avatars, which are computer user's representations of himself/herself or alteration of their egos".	CG software MAYA Second life	Eye mechanism learning
4	Marmaridis & Griffith (2009)	Australia	Australia	3	"The Metaverse is a virtual world, described in Neal Stephenson's (1992) science fiction novel Snow Crash, where humans, as avatars, interact with each other and software agents, in a three-dimensional space that uses the metaphor of the real world. The word Metaverse is a compound of the words "meta" and "universe"	Second life	Technical solution

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
5	Fernandez-Gallego et al. (2010)	Spain	South America	3	"To enrich and improve participant interactions, the usage of 3D teaching scenarios in virtual worlds (aka metaverses) seems to be a promising solution".	"…a service-oriented architecture that facilitates the execution of learning units, based on the IMS Learning Design specification (IMS LD), in a metaverse platform like Second Life or OpenSim".	Technical solution
6	Getchell et al., (2010)	United Kingdom (UK)	Europe	4	"As an emerging class of technologies, metaverses are a relatively new development, with some of the more mature examples such as There and Second Life being released within the last 5–6 years".	Second Life	Archaeology education, game based learning (GBL)
7	Kanematsu et al., (2010)	US, Korea & Japan	Cross-region	4	"Metaverse is one of the social media characterized as a synchronous, 3D virtual world resembling reality". "Metaverse can be defined as a virtual three dimensional space where the character called avatar is active instead of a person. As a commercial service of Metaverse, Second Life (of Linden Research Inc. in San Francisco, California, USA) is the most well known".	Second Life	E-Learning, multilingual problem based learning

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
8	Nakahira et al., (2010)	Japan	Asia	3	"The metaverse is a virtual world described by Neal Stephenson in his novel Snow Crasy. Human active as avator, which is a computer user's alter ego, on metaverse".	Second Life	Problem based learning (PBL)
9	Jaffurs (2011)	US	North America	4	"I define the Metaverse as a virtual embodied world. Usually associated with gaming, this world allows players to access a website and experience a virtual three-dimensional space where they can interact with others".	Second Life	Music education
10	Tamai et al., (2011)	Japan	Asia	4	"SecondLife (SL), the most popular metaverse service by Linden Lab, provides the environment for constructing online campuses, virtual museums, or place for academic conferences on the internet. Avatar, which is a user's agent in the 3D space, can walk around the virtual space composed by electronically constructed objects, and interact with other avatars".	Second Life	Situated learning, model of learning by teaching
11	Kanematsu et al., (2012)	Japan	Asia	4	"For this project, we utilized Metaverse as virtual space where the e-learning class activity was available… Metaverse is a three dimensional virtual world where avatars do everything on behalf of the participants…. Therefore, Second Life as Metaverse was chosen as a virtual environment".	Second Life	Engineering education, PBL

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
12	Vernaza et al. (2012)	Panama	South America	3	"Metaverse is a virtual space where people interact socially and economically using avatars without experiencing the real world constraints such as time and distance". "For eduaction, metaverse is a space for learning activities generated from classcial e-learning content management system(LCMS). The idea of using the Metaverse (virtual worlds) as a space for the development of learning activities".	OpenSim	E-Learning retaled to electronics
13	Yu et al. (2012)	US	North America	1	"Metaverses are immersive three-dimensional virtual worlds (VWs) in which people interact as avatars with each other and with software agents, using the metaphor of the real world but without its physical limitations". "One of examples of a metaverse is Second Life"	NA	Virtual teams in healthcare
14	Tarouco et al., (2013)	Brazil	South America	3	"The VLL is hosted in the virtual world (or metaverse) OpenSim, which is based on free software derived from the proprietary tool Second Life, widespread in the context of virtual worlds".	OpenSim, E2D, Voki, HotPotatoes, SketchUp	Mathmatics teachning and learning

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
15	Torres-Arias and Trefftz (2013)	Colombia	South America	4	"……immersive virtual environments including Second Life. In relation to the teaching and learning processes, these metaverses, as they are ca…." "Virtual worlds or metaverses are simulated spaces of social interaction on the web that aims to mimic the real world in their geographical, sociographic, economic and communication, but overcoming the limitations of the real physical world. These virtual worlds can simulate real-world laws or have their own rules. In virtual worlds inhabitants are represented by avatars".	Second Life	Language learning
16	Kanematsu et al., (2014)	Japan	Asia	4	"The lecture was given to them through the virtual class in Metaverse (Second Life). Metaverse is the virtual 3-Dimensional World".	Second Life	Blend education
17	Barry et al., (2015)	Japan	Asia	4	"Metaverse is a virtual three-dimensional world where avatars do everything on behalf of us". "It is located on the virtual island owned by Nagaoka University of Technology (NUT) in Second Life, a well-known type of Metaverse".	Second Life	PBL

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
18	Alvaro-Farfan et al., (2020)	Japan	Asia	4	"…the purpose of this article is to study the usage of virtual worlds (Metaverses) as evaluation tool". "The virtual worlds present several projections towards interaction with users through direct contact, immersion when losing contact with reality and imagination for the construction of new worlds and the production of virtual realities".	Moodle and OpenSim	Evaluational tool
19	Díaz et al., (2020)	Colombia	South America	3	"…design, development and implementation of a virtual or metaverse world in an educational environment under the Scrum methodology…" "Metaverse is the future virtual society where users consist in the presence of avatar, experiencing different contexts of ways of life. Virtual world for higher education is a particular case of metaverse. It enables interactive and immersive teaching–learning process underpinned by diverse ICTs". "The virtual world market has been diversifying into augmented reality applications, mirror worlds, metaverses and Lifelogging platforms"	OpenSim	Technical solution to hybrid education
20	Suzuki et al. (2020)	Japan	Asia	3	"Metaverse is a virtual three-dimensional world where avatars on behalf users in real world".	Second Life	Technical solution for sharing analytical instrument

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
21	Duan et al., (2021)	China	Asia	1	"The expected metaverse should be a realistic society with more direct and physical interactions, while the concepts of race, gender, and even physical disability would be weakened, which would be highly beneficial for society. Metaverse is a combination of "meta" (meaning beyond) and the stem "verse" from "universe", denoting the next-generation Internet in which the users, as avatars, can interact with each other and software applications in a three dimensional (3D) virtual space….There has been approximately 30 years' development behind the evolution of this term".	Unity15, Blender, FISCO-BCOS	A macro-level metaverse architecture and a prototype of a university campus
22	Siyaev and Jo (2021a, 2021b)	Korea	Asia	3	"Metaverse is coming. The world started to experience an extraordinary mixedreality (MR) digital place inside of the physical world where people seamlessly get to gether and interact in millions of 3D virtual experiences".	Unity, Microsoft HoloLens 2	Aircraft maintaince education-collaborative learning
23	Siyaev and Jo (2021a, 2021b)	Korea	Asia	3	"The Metaverse as a term is used to describe the concept of a future iteration of the internet, made up of persistent, shared, 3D virtual spaces linked into a perceived virtual universe".	Unity, Microsoft HoloLens 2	Training and education of aircraft maintenance

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
24	Akour et al. (2022)	Cross-country Collaboration	Cross-region	2	"Accordingly, metaverse can be defined as a worldthat has virtually enhanced physical reality and space. It is an infusion of real and physical universe that allows users to imagine multiple and myriad digital mirrors of the real world, both existent and non-existent, for a variety of purposes".	NA	Investigating students' perceptions of a metaverse
25	Almarzouqi et al., (2022)	United Arab Emirates (UAE)	Asia	2	"Metaverse (MS) is a digital universe accessible through a virtual environment. It is established through the merging of virtually improved physical and digital reality". "Through the interactivity characteristics, Metaverse ensures users' virtual platform interactions. Interactivity ensures real-time, interoperable, and synchronous learning. The MS allows users to interact and have continuous connections with the virtual world without leaving the real world…. Metaverse also allows unlimited users to experience a real-time rendered 3D virtual world with an individual sense of presence through the corporeity feature".	NA	NA
26	Chen et al., (2022a)	China	Asia	4	"…metaverse provided a realistic online platform giving learners a sense of social presence to build a high level of trust with collective accountability within teams, which offers a good environment for online group learning".	NetDragon	Blended teaching model in metaverse

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
27	Chen et al., (2022b)	China	Asia	3	"However, metaverse would expand immersive virtual world and may be the future of the internet, making it more immersive, interactive and collaborative". "Metaverse includes virtual reality which creates a simulated world and augmented reality that combines aspects of the digital and physical worlds as well as digital economy where users can create, buy, and sell good". "The metaverse roadmap categorizes the metaverse into 4 types: AR, lifelogging, mirror world, and VR".	NA	Medical education, situated learning
28	Dahan et al., (2022)	Korea	Asia	1	"Metaverse is a vast term that can contain every digital thing in the future". "Metaverse is the most recent technology that is still not fully explored nor fully implemented yet".	NA	NA
29	Guo & Gao (2022)	China	Asia	4	"The metaverse represents the latest stage of the development of visual immersion technology. Its essence is an online digital space parallel to the real world, which is becoming a practical field for the innovation and development of human society".	NA	English teaching

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
30	Jovanović and Milosavljević (2022)	Serbia	Europe	3	"Moreover, new mediums that we can use for online learning such as metaverse or virtual worlds (VWs) platforms are emerging. We can define VWs as follows: "Simulated persistent space based on the interaction with a computer, inhabited by several users, who are represented by iconic images called avatars, who can communicate with each other in a synchronized way"	Unity game engine, MicroLesson	NA
31	Khansulivong et al., (2022)	Laos	Asia	4	"The Metaverse is a virtual simulation that participants interact themselves with avatars created for getting the experiences or creating the second life in a 3D environment without timing and space limitation by themselves". "The Metaverse integrates these worlds as a network of interconnected experiences and applications, devices and products, tools and infrastructure, people using the internet for all activities such as entertainment, economy, and access to services". "…the development of activities in the Metaverse or dreaming of the full entertainment or full learning course in the future. Besides that, The Metaverse can take people back to the past by simulating the places of history or antique which idea for comparison between present lesson and knowledge in the past".	Meta Horizon	Agricultural experiment learning

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
32	Lee and Hwang (2022)	Korea	Asia	4	"Metaverse is virtual enhanced reality in which individuals congregate via avatars for human interaction and cultural exchanges.This research sheds new lights on the role of the metaverse (emerging technology as a fully realized digital world)".	Frame VR, Cospaces Edu	Teacher trainning
33	Lee et al., (2022)	Korea	Asia	4	"A metaverse—a portmanteau of 'meta' and 'universe'—is a three-dimensional virtual world that incorporates social and economic activity. In a metaverse, interaction is possible using a virtual avatar that acts as an agent for each user. The term metaverse first appeared in the 1992 novel "Snow Crash" by Neal Stephenson. A metaverse is a virtual world that enables socioeconomic activities analogous to those in the real world. In 2007, the non-profit technology organization Acceleration Studies Foundation (ASF) published the "Metaverse Roadmap: Pathways to the 3D Web", which defines a metaverse as the convergence of a virtually enhanced physical reality with a physically sustainable virtual space. The ASF has defined two main characters for a metaverse: the spectrum of technologies and applications, from augmentation to simulation, and the spectrum of identity in the form of digital profiles, such as avatars representing users".	Unity, photon, HTC Vive Pro Eye, Oculus Rift S	Aircraft maintaince education

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
34	Mustafa (2022)	Jordan	Asia	2	"The Metaverse is a post-reality universe, a perpetual multi-user environment th at combines physical reality and digital virtuality. It is based on the convergence of technologies that enable multisensory interactions with virtual environments, digital objects, and people, such as virtual reality (VR) and augmented reality (AR). As a result, Metaverse is a web of social, networked immersive environments on persistent multi-user platforms. It allows for real-time, embodied user communication and dynamic interactions with digital artifacts. Its first incarnation was a web of virtual worlds between which avatars could teleport. …The modern Metaverse includes social, immersive VR platforms that are compatible with massive multiplayer online video games, open game worlds, and AR collaborative spaces".	NA	NA

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
35	Park and Kim (2022)	Korea	Asia	1	"Previously, the metaverse only talked about the online virtual world, but today, in the postpandemic world, it has become a medium that connects the on/offline realms centering on augmented reality and virtual reality technology. Metaverse was being developed based on virtual reality before the COVID-19 pandemic, but attracted renewed attention once it struck to meet the limitations of external activities and individual needs. It is a rapidly expanding concept. Acceleration Studies Foundation (ASF), a non-profit technology research organization, published a metaverse road map in 2007 and presented four classification criteria for metaverse".	NA	NA
36	Suh and Ahn (2022)	Korea	Asia	2	"The term 'metaverse' refers to an immersive digital environment where one can interact with virtual avatars. Specifically, the metaverse consists of a VW, a mirror world (MW), life logging (LL), and AR".	NA	Students' usage in daily life, not a particular application about education-Learner-Centered Constructivist Education

Article ID	Authors & year	Country	Region	Group No	Definition (quotes from the reviewed articles)	Platform	Application
37	Talan and Kalinkara (2022)	UAE	Asia	2	"Although the Metaverse refers to an immersive 3D world, concepts regarding the nature and organization of the Metaverse have changed over time. According to the general trend, the Metaverse is a network of interconnected virtual worlds rather than a stronger version of a single virtual world (Dionisio et al., 2013). Therefore, to understand the Metaverse better, first, it is necessary to understand the concept of virtual worlds. Virtual worlds are environments that contain three-dimensional graphical worlds and are a kind of simulation of physical reality (Metcalf et al., 2011)".	NA	NA

The designation of 'Country' is determined by the country in which the experiment is conducted, rather than solely by the country of the authors or the participants. 'NA' means not applicable

Appendix B

Coding results of reviewed articles (part 2)

Article ID	Authors & year	Subject	Discipline	Cohort	Formal/Informal education	N	Effect			
							Enrich learning experience	Increase learning engagement	Enhance learning outcomes	Facilitate the development of social skills
1	Chris Collins (2008)	–	–	Higher Ed	–	–				
2	Davis et al., (2009)	–	—	–	–	–				
3	Itoh et al., (2009)	Biomedicine	STEM	Across age groups	Informal	19	√	√	√	
4	Marmaridis & Griffith (20090	-	–	–	Formal	–				
5	Fernández-Gallego et al., (2010)	–	–	–	Formal	–				
6	Getchell et al., (2010)	Archaeology	Non-STEM	Higher Ed	Formal	–	√	√		
7	Kanematsu et al., (2010)	Multilingual discussion	Non-STEM	High School and Higher Ed	Informal	9				√
8	Nakahira et al., (2010)	–	–	Higher Ed	Formal	–				
9	Jaffurs (2011)	Music	Non-STEM	High school	Formal	3		√		
10	Tamai et al., (2011)	Japanese language and culture	Non-STEM	Higher Ed	Informal	6			√	
11	Kanematsu et al., (2012)	Nuclear safety	STEM	Higher Ed	Formal	3		√	√	
12	Vernaza et al. (2012)	Electronics	STEM	Higher Ed	Formal	–				
13	Yu et al. (2012)	–	–	–	–	–				
14	Tarouco et al., (2013)	Math	STEM	Higher Ed	Formal	–				

Article ID	Authors & year	Subject	Discipline	Cohort	Formal/Informal education	N	Effect			
							Enrich learning experience	Increase learning engagement	Enhance learning outcomes	Facilitate the development of social skills
15	Torres–Arias and Trefftz(2013)	English	Non-STEM	Higher Ed	Formal	26		√	√	
16	Kanematsu et al., (2014)	Radioactivity and nuclear safety	STEM	Elementary school	Formal	6			√	
17	Barry et al., (2015)	Math	STEM	Higher Ed	Formal	3		√		
18	Alvaro–Farfan et al.,(2020)	Math, language and literature, chemistry	STEM & non-STEM	Higher Ed	Formal	–			√	
19	Díaz et al. (2020)	Math	STEM	Higher Ed	Formal	–				
20	Suzuki et al. (2020)	Engineering	STEM	KOSEN	Formal	–				
21	Duan et al., (2021)	–	–	Higher Ed	–	–				
22	Siyaev and Jo (2021a, 2021b)	Aircraft maintaince	STEM	–	Formal	–				
23	Siyaev and Jo (2021a, 2021b)	Aircraft maintaince	STEM	Higher Ed	Formal	–				
24	Akour et al. (2022)	–	–	Higher Ed	–	862				
25	Almarzouqi et al.,(2022)	–	–	Higher Ed	–	1858				
26	Chen et al., (2022a)	Medicine	STEM	Higher Ed	Formal	–		√		√
27	Chen et al.,(2022b)	Medicine	STEM	Higher Ed	Formal	–				
28	Dahan et al., (2022)	–	–	Higher Ed	–	–				
29	Guo & Gao (2022)	English	Non-STEM	–	Formal	–		√		
30	Jovanović and Milosavljević (2022)	-	-	-	Formal	-				

Article ID	Authors & year	Subject	Discipline	Cohort	Formal/Informal education	N	Effect			
							Enrich learning experience	Increase learning engagement	Enhance learning outcomes	Facilitate the development of social skills
31	Khansulivong et al.,(2022)	Agriculture	STEM	Higher Ed	Formal	29		√		
32	Lee and Hwang (2022)	Teacher training	Non-STEM	Higher Ed	Formal	51				
33	Lee et al., (2022)	Aircraft maintenance	STEM	Higher Ed	Formal	40	√		√	√
34	Mustafa (2022)	–	–	Higher Ed	–	–				
35	Park and Kim (2022,	–	–	–	–	–				
36	Suh and Ahn (2022)	–	–	Elementary school	–	336				
37	Talan and Kalinkara (2022)	–	–	–	–	34				

"N" denotes the number of participants in the corresponding study. KOSEN is the education stage between high school and university education in Japan

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